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WORLDWIDE DISTILLATE FUEL QUALITY AND ENGINE TECHNOLOGY THROUGH THE YEAR 2010

INTERIM REPORT
TFLRF No. 349

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Defense Energy Support Center
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Under Contract to

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Contract No. DAAK70-92-C-0059

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13. ABSTRACT (Maximum 200 words)
This report gives the results of a program to assess the potential changes in future petroleum refining technology and the potential changes in the properties of future commercial, distillate, marine fuels as well as the Navy's fuel for shipboard propulsion (F-76) worldwide, forecasted over the next ten to twelve years. Also, assess the future potential changes in gas turbine and diesel engine technology and how these changes will affect future Navy fuel quality demands. Assess the future potential changes in marine and coastal environmental regulations worldwide and identify how these regulatory changes may impact Navy engine and fuel requirements. And, combine the results of the earlier three phases to produce a consolidated overview of the potential changes that may impact future property requirements.

To accomplish these goals, surveys of both engine manufacturers and oil companies were conducted, historical data were collected and analyzed, and pertinent literature was reviewed. The report gives specific conclusions regarding future fuel quality and future engine technology.

14. SUBJECT TERMS

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FOREWORD/ACKNOWLEDGMENTS

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This work was performed by the U.S. Army TARDEC Fuels and Lubricants Research Facility (TFLRF) located at Southwest Research Institute (SwRI), San Antonio, Texas, during the period June 1999 through September 2000 under Contract No. DAAK70-92-C-0059. The work was administered by the U.S. Army Tank-Automotive RD&E Center, Petroleum and Water Business Area, Warren, Michigan. Mr. Luis Villahermosa (AMSTA TR-D/210) served as the TARDEC contracting officer's representative.

EXECUTIVE SUMMARY

Problem: Because of changing environmental regulations worldwide, the average quality of middle distillate fuel around the world is also changing. Most of the changes in fuel quality are improvements, such as mandatory reductions in sulfur levels. However, the refining processes used to produce these low sulfur fuels can concomitantly reduce the lubricating properties of the fuel. Lower lubricity fuels can, in turn, cause increased wear in fuel-wetted engine components.

Objective: Conduct a study to assess the potential changes in the properties of commercial distillate marine fuels over the next ten to twelve years. Also, determine what future engine technology changes may be applicable to Navy needs and should therefore be considered as part of future Navy engine development.

Importance of Project: Will assure that current fuel specifications will continue to provide adequate protection of Navy, Military Sealift Command, and Coast Guard shipboard combustion and fuel handling equipment. Will also provide sufficient lead-time for potential revision of these specifications and /or development of new commercial and/or military specifications to meet the projected fuel property changes in the global fuels marketplace.

Technical Approach: Review historical fuels property data and distribute a survey questionnaire to selected fuel producers. Review current Navy, Military Sealift Command, and Coast Guard shipboard engine and fuel handling equipment. Distribute a survey questionnaire to diesel and gas turbine engine manufacturers. Review current and future environmental regulations and assess the potential impact on both current and future fuels and engines. Review above findings with representatives of both the refining industry and engine manufacturing industry for their comments.

Accomplishments: Conducted surveys of both the refining industry and engine manufacturer members. Conducted a review of present and expected future environmental regulations. Reviewed historical marine distillate fuel, and other fuel, property data.

Military Impact: Developed recommendations for future Navy engine development projects and also possible future Navy fuel specifications and fuel procurement activities.

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LIST OF ACRONYMS AND ABBREVIATIONS

AAMA	American Automobile Manufacturers Association
ACEA	European Automobile Manufacturers Association
API	American Petroleum Institute
ASTM	American Society of Testing and Materials
ATAS	Association of Turkish American Scientists
bbl/d	Barrels Per Day
btms	Bottoms
°C	Degrees Celsius
CAAA	Clean Air Act Amendments
CARB	California Air Resources Board
CIS	Commonwealth of Independent States
CO	Carbon Monoxide
CODAG	Combined Diesel and Gas Turbine
CODOG	Combined Diesel or Gas Turbine
DCI4A	Corrosion inhibitor lubricity additive for aviation and motor gasolines, jet fuels and other distillate fuels. Widely approved and preferred for use in jet fuels.
DESC	Defense Energy Supply Center
DLA	Defense Logistics Agency
DMA	Grade of Marine Distillate Fuel Under ASTM D2069 and/or ISO 8217
DME	Dimethyl Ether
DoD	Department of Defense
DOE	Department of Energy
EEV	Electronic Engine Valve
EGR	exhaust gas recirculation
EIA	Energy Information Administration
EMA	Engine Manufacturers Association
EPA	Environmental Protection Agency
F-76	Navy Shipboard Propulsion Fuel, Military Specification MIL-F-16884J Fuel, Naval Distillate (NATO F-76)
FQP	Fuels Qualification Procedure
FQP1A	Recommended Guideline on Premium Diesel Fuel
GVDF	ground vehicle diesel fuel
HMGO	heavy marine gas oil
IFO	intermediate fuel oil
ISO	International Organization for Standards
Kg/m^3	Kilograms per meter cubed
max	maximum
MDF	marine diesel fuel
mg/L	milligram per Liter
mg/100ml	milligram per 100 milliliters
MGO	Marine Gas Oil
min	minimum

mm^2/sec	millimeters squared per second
mmb/d	Million Barrels Per Day
MSC	Military Sealift Command
NAVSEASYSCOM	Naval Sea Systems Command
NIPER	National Institute for Petroleum and Energy Research
NO_x	Oxides of Nitrogen
N_2	Nitrogen
NSFO	Navy Special Fuel Oil
NSWCCD	Naval Surface Warfare Center Carderock Division
OPNAV	Office of the Chief of Naval Operations
PD	Purchase Description
PdVSA	Petroleos de Venezuela, South America
PM10	Particulate Matter exceeding 10 microns in diameter
PPM	parts per million
SLBOCLE	Scuffing Load Ball on Cylinder Lubricity Evaluator
SO_2	Sulfur Dioxide
SwRI	Southwest Research Institute
TARDEC	Tank-automotive Research, Development and Engineering Center
TFLRF	TARDEC Fuels and Lubricants Research Facility
USCG	U. S. Coast Guard
vol%	volume percent
wt%	weight percent

I. BACKGROUND

In 1994, the office of the Under Secretary of Defense for Acquisition and Technology issued a directive to reduce the use of military specifications, if feasible, as a cost savings to the Federal Government. In response to this directive, the Defense Energy Support Center (DESC) established a commercial specification initiative. In support of the initiative, the 1996 Worldwide Survey of Distillate Fuels[1] was undertaken to assess the degree to which distillate fuels available in the global commercial marketplace can be used aboard Navy ships. The survey also looked at fuels for Army ground equipment. Fuel samples were gathered from 41 of 44 selected sample sites worldwide. The properties of the fuels collected were analyzed and these properties were compared to the requirements of Military Specification MIL-F-16884J, Fuel, Naval Distillate, (NATO F-76) and the NAVSEASYSCOM (Naval Sea Systems Command) Purchase Description (PD) for Marine Gas Oil (MGO), NSN 9140-01-313-7776 (domestic) and 9140-01-417-6843 (overseas). Only about 10% of the fuel samples collected satisfied all 26 property requirements of MIL-F-16884J, while about 30% of the fuel samples satisfied all 13 property requirements of the PD. Furthermore, of about one fifth of the fuels that satisfied the PD requirements, those fuel properties which were <u>not</u> covered by the PD showed the potential to cause significant shipboard operational problems. These were properties covered by the F-76 specification.

Such a problem occurred in December 1996. The U.S. Coast Guard (USCG) experienced severe incompatibility/instability problems aboard a cutter operating off the US East Coast with fuel meeting the requirements of the NAVSEA MGO PD. The Coast Guard was required to use the PD because F-76 and F-44 (JP-5) were not available. Additionally, changes in commercial distillates due to environmental requirements, both in the US and abroad, have impacted the quality of F-76. F-76 fuel has requirements for storage stability that are not reflected in any commercial specification for marine fuels. It also has different limits and requirements for sulfur and additives. Knowledge of what refineries are doing with distillate products that could significantly affect F-76 quality further is needed by DESC in order to adjust buying strategies and storage capabilities accordingly. In the past, DESC has reacted proactively to address changes in the F-76 specification to the benefit of assuring quality product to its customers. Although it is primarily the responsibility of the NAVSEA, as the specification activity, to address and compensate for such changes, overall reduction in the OPNAV budget for studies necessary to collect and generate data has constricted NAVSEA's ability to do so in recent years.

A 1996 Worldwide Survey provided an excellent snapshot of the properties of current, commercial, distillate, marine fuels. However, it did not address future potential changes in fuel properties, the elements that can drive these changes, or the impacts these may have on Navy or USCG shipboard combustion. Nor did it address the storage stability of fuel to meet war reserve requirements. Therefore an assessment of the potential changes in the properties of commercial distillate marine fuels over the next ten to twelve years is required to redefine both the Navy's Shipboard Fuels Qualification Procedure (FQP) program and DESC's procurement, storage and distribution practices. Such a redefinition will assure that current specifications will continue to provide adequate protection of Navy, Military Sealift Command (MSC), and Coast Guard shipboard combustion and handling equipment. It will also provide sufficient lead-time for potential revision of these specifications and/or development of new commercial and/or military specifications to meet the projected fuel property changes in the global fuels marketplace.

II. SCOPE OF WORK

The work was divided into four tasks:

- **Task 1 Changes in Refining Technology:** Assess the potential changes in future petroleum refining technology and the potential changes in the properties of future commercial, distillate, marine fuels as well as F-76 worldwide, forecasted over the next ten to twelve years.

- Task **2 Changes in Diesel Engine and Gas Turbine Technology:** Assess the future potential changes in gas turbine and diesel engine technology and how these changes will affect future Navy fuel quality demands.

- **Task 3 Changes in Environmental Regulations:** Assess the future potential changes in marine and coastal environmental regulations worldwide and identify how these regulatory changes may impact Navy engine and fuel requirements.

- **Task 4 Meeting of Government and Industry Representatives:** Combine the results of the earlier three phases to produce a consolidated overview of the potential changes that may impact future property requirements.

III. APPROACH

A. Task 1: Changes in Refining Technology

Past work in the area of determining future quality, done by the National Institute for Petroleum and Energy Research (NIPER) for DESC, was reviewed and applied to the current task. Historical fuel property data were acquired from the 1996 Worldwide Survey of Distillate Fuels, the NSWCCD F-76 data base, and commercially available databases to develop a baseline for extrapolation of future fuel properties. Historical information on petroleum processing technology developments was also gathered to establish historical trends and develop a baseline for extrapolating future developments.

A survey questionnaire was developed with DESC guidance and distributed to identified refiners, fuel suppliers and fuel-marketing experts to solicit their input about future fuel quality and processing changes. Information on changes in refinery capabilities and production as well as divergence in refinery practices due to mounting environmental and investment pressures, was gathered and used to forecast changes in the availability and quality of commercial distillate marine fuels and F-76.

B. Task 2: Changes in Diesel Engine and Gas Turbine Technology

Existing Navy, Coast Guard and MSC data of current shipboard combustion and fuel handling equipment were reviewed to assess current equipment/fuel requirements. A survey questionnaire was then developed and distributed to manufacturers of current Navy, Coast Guard and MSC shipboard gas turbine and diesel engines to solicit their opinions and concerns about potential future developments in shipboard engines, the fuel property requirements of future equipment, and the forces driving these changes. This information was combined to form an equipment industry view of potential future developments in shipboard engines and their fuel requirements.

C. Task 3: Changes in Environmental Regulations

The following sources of information were reviewed:

- Environmental regulations from specific U. S. local areas, coastal states, and national jurisdictions.

- Environmental regulations of international jurisdictions.
- Commercial information databases, law reviews, periodical literature, conference papers, and studies by governmental agencies and private companies.

The reviewed regulations were ranked to form a hierarchy of most to least rigorous and also to identify trends in the development of worldwide environmental issues. A summary of the environmental regulations is presented in Appendix A. The full review is published as a separate report.[2] The primary focus of this review is residual fuels; distillate fuel regulations are secondary.

D. Task 4: Meeting of Government and Industry Representatives

A meeting of government, marine engine, and fuel industry representatives was convened to review the responses to the two survey questionnaires as well as the results of the environmental regulation survey. Attendees at the meeting were asked to provide comments on the reported findings, which were, in turn, used in the preparation of this report.

IV. THE IMPORTANCE OF AUTOMOTIVE (ON-HIGHWAY) DIESEL FUEL REGULATIONS

It should be noted that at this point in time the majority of environmental regulations for marine fuels and marine applications are focused on heavier fuels. This is because the majority of commercial ships in the world still operate on heavy fuel. In contrast, greater than 90% of ships in the U. S. Navy fleet operate on middle distillate fuels, primarily F-76. [*All the vessels in the fleet can operate on F-76 but for logistical reasons, some operate on either JP-5 or MGO PD.*] F-76 much more closely resembles automotive diesel fuel than heavy marine fuel. The significance of this becomes evident in regions where fuel refiners/distributors provide only one grade of fuel to meet middle distillate (diesel) fuel requirements. In such instances, the fuel will be produced to meet the specification of the fuel that is in greatest demand. Most often that fuel is automotive diesel fuel. Therefore, if the supplier has an automotive fuel that meets the Navy's specifications, he will offer that fuel for sale to the Navy. The end result is that the Navy contracts for F-76 and often obtains a fuel that was originally produced to meet local automotive diesel specifications. For this reason, it is important to be aware of changing requirements for automotive diesel fuel throughout the world. An example of this was the Environmental Protection Agency (EPA) mandated reduction in total sulfur that became effective October 1993. Fuel intended for non-automotive uses was required to contain a blue dye to show that the fuel

had not been assessed taxes. F-76 fuel falls into the category of non-automotive fuel and thus should be dyed blue. However, the Navy soon discovered that the blue dye could cause storage stability problems in F-76. Also, the Federal Aviation Administration found that aircraft could be misfueled with blue-dyed diesel fuel because the fuel resembles aviation gasoline. In addition to the storage stability problem with blue dye, engine manufacturers, because of the expense, could not show the impact of red dyed F-76 on combustion equipment. By demonstrating that the Navy could adequately segregate their fuels from commercial transportation and storage, they were granted a waiver from the requirement to dye their fuel red. Hence, an EPA "enforcement discretion" was granted the Navy. Fuel purchased under the MGO PD, however, has red dye in it and is used onboard ship; but, only about 2-4% of the time.

Currently, regulatory agencies throughout the world are requiring reductions in the total sulfur of automotive diesel fuels and/or considering additional reductions. Many countries already set maximum sulfur levels, for automotive diesel, at 500 ppm maximum. Some countries, such as Sweden, have set the requirements an order of magnitude lower. Throughout Europe and the United States, maximum sulfur limits of 10 to 30 ppm are being seriously considered; there is considerable agreement that such regulations will be in place in the near future.

Because of the way that diesel fuels are produced and distributed throughout much of the world, mandated changes in automotive diesel fuel quality will show up in middle distillate marine fuels in many parts of the world. The experiences of the automotive diesel fuel users in these areas should also be considered as sources of information regarding potential problems (or benefits) associated with the use of these fuels. One potential problem that is sometimes associated with these cleaner, more highly refined diesel fuels is fuel lubricity.

V. REFINING TECHNOLOGY

A. Recent History

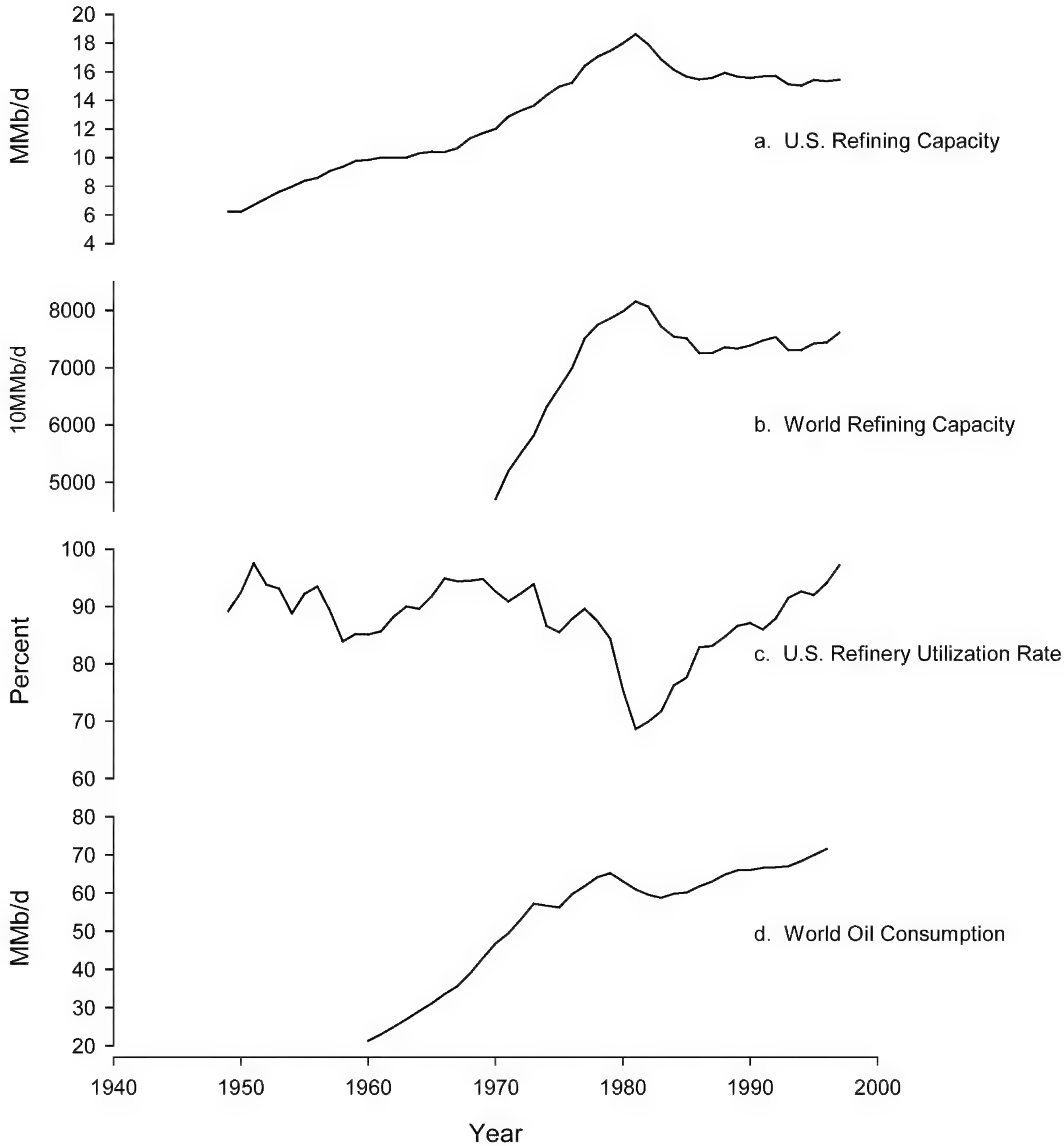
From its beginning through the late 1970's, the refining industry enjoyed relatively slow, steady growth. In the late 1970's and early 1980's, refining capacity continued to grow. At the same time, market demand, as indicated by refinery utilization rates, began to drop. This is shown in Figure 1, which shows plots of U.S. and world refining capacity, U.S. refinery utilization rates, and world oil consumption. Utilization rates were at a low point in the 1981-1982 time frame and then began to

climb as demand increased (with falling prices) and capacity decreased. Since the late 1970's and early 1980's, the number of operational U.S. refineries has fallen from a high of 324 in 1984 to 164 in 1997. Figure 2 is a plot of the number of operational U.S. refineries for the years 1949 to 1997. According to the DOE:

> "…the remaining refineries have improved their efficiencies and flexibility to process heavier crude oils by incorporating improved technology and by adding upgrading units downstream of the distillation units. In the 1990's, investments were driven mainly by new clean fuel requirements and the need to improve on the environmental impacts of operations."[3]

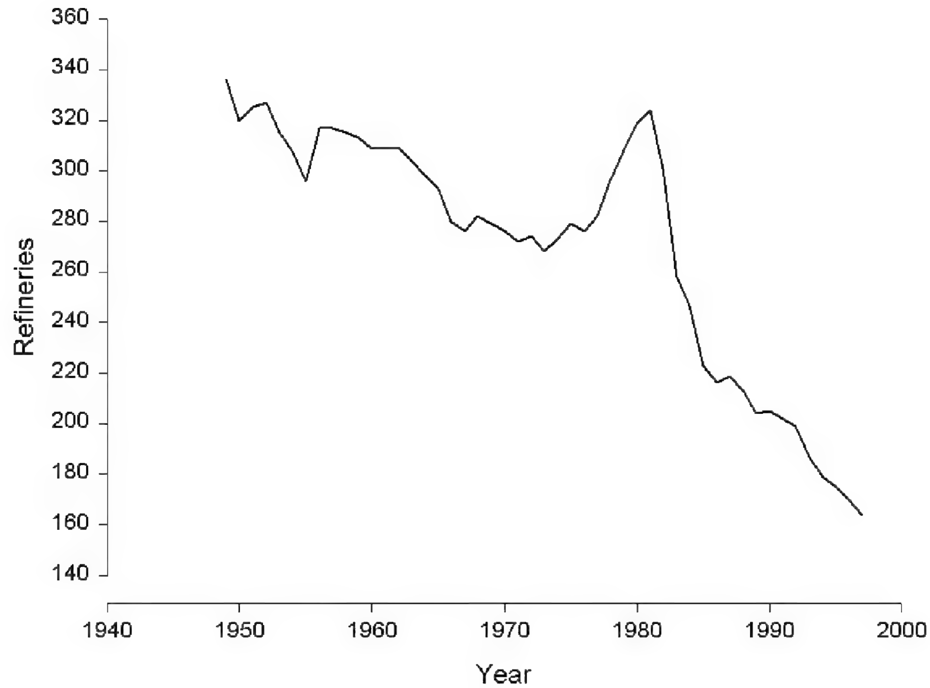
The decreasing quality of U.S. refinery crude runs is demonstrated by Figure 3. This is a plot of the weighted-average total sulfur and API gravity of all U.S. crude runs for the years 1985 to 1997. Figure 3 demonstrates that the weighted-average total sulfur has been generally increasing and the API gravity has decreased (although the rate of decrease has slowed over the past several years). Although the average API gravity has continued to fall for many years, refinery production of heavier products has decreased. The DOE reports that in 1980, heavy residual fuel represented 11.7% of the U.S. product barrel. By 1985 the residual fuel yield fell to 7.1%. In 1995 the yield of heavy residual fuel was only 5.4%.[4]

The decreasing percentage of heavy material in spite of decreasing API gravity is indicative of the conversion of many refineries to allow increased conversion of bottoms. The data in Table 1 show the increase in the ability of U.S. refineries to process crude oil bottoms. As shown in Table 1, coker unit capacity grew rapidly during the 1980's but the rate of growth has slowed some since 1990. According to the Energy Information Administration (EIA), throughout 1996, the utilization "rates for cokers [were] the highest of all the process units" they tracked.[5]



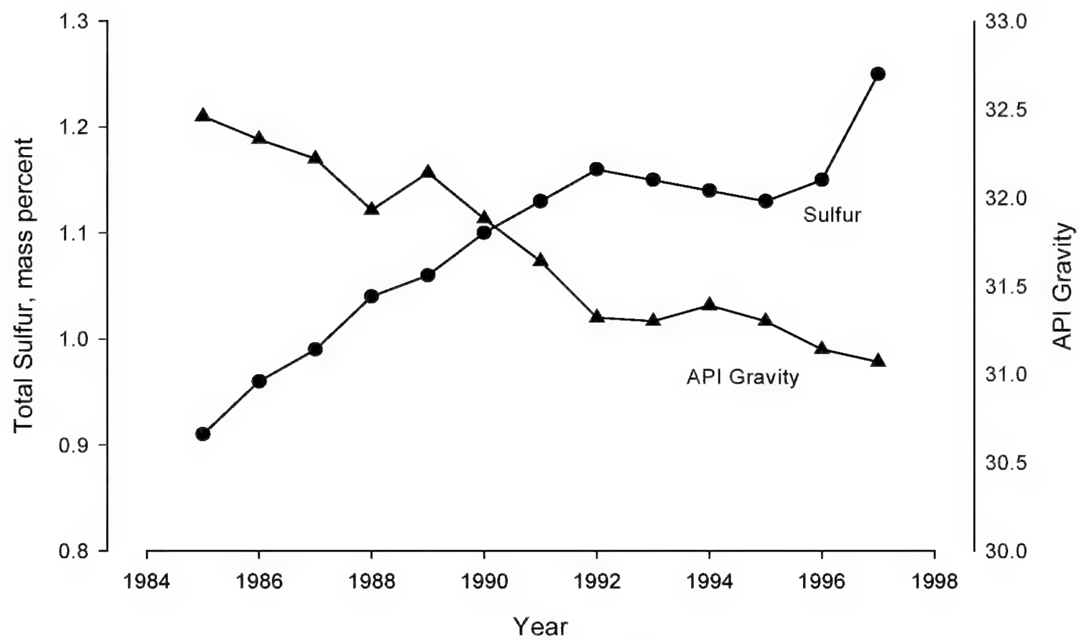
Source: U.S. Department of Energy, Energy Information Administration
a, b, & c: *Annual Energy Outlook, 1998*
d: *Annual Energy Review, 1998*

Figure 1. Refining and Oil Consumption Statistics



Source: U.S. Department of Energy, Energy Information Administration,
Annual Energy Outlook, 1998

Figure 2. Number of U. S. Refineries



Source: U.S. Department of Energy, Energy Information Administration,
Annual Energy Outlook, 1998.

Figure 3. Annual Weighted-Average, Total Sulfur and API Gravity for U.S. Refinery Crude Runs

Year	Number of Operable Refineries	Operable Crude Oil Distillation (MB/SD*)	Fresh Feed Catalytic Cracking (MB/SD)	Coking (MB/SD)	Hydro-cracking (MB/SD)	Hydro-treating (MB/SD)	Alkylation (MB/SD)	Isomerization (MB/SD)
1981	324	18,621	5,543	1,021	909	8,487	974	131
1985	223	16,504	5,232	1,407	1,053	8,897	917	219
1990	205	16,507	5,441	1,549	1,282	9,537	1,030	456
1995	175	16,326	5,583	1,785	1,386	10,916	1,105	502
1996	171	16,169	5,599	1,842	1,385	11,050	1,122	505
Change 1981-1996	-153	-2,452	56	821	476	2,563	148	505
Percent Change 1981-1996	-47%	-13%	1%	80%	52%	30%	15%	285%

Table 1. U.S. Refinery Capacity (as of January 1 of each year)

*MB/SD = thousand barrels per stream day

Source: U.S. Department of Energy, Energy Information Administration, *Annual Refinery Report., 1997*

The Clean Air Act Amendments (CAAA) of 1990 are the force behind most refinery investments since that time. New federal (and state in the case of California) gasoline and diesel fuel requirements necessitated even greater improvements in fuel quality. Starting in October 1993, the allowable total sulfur content of on-highway, automotive diesel fuel was reduced from 0.5 mass percent to 0.05 mass percent. According to the DOE, this requirement for reduced sulfur caused an increase of 827,000 barrels per day (bbl/d) in middle distillate hydrotreating capacity between 1990 and 1995.[6]

B. Future Trends in Refining Technology

All expectations are that worldwide demand for petroleum, and hence refining capacity, will steadily increase through at least 2010 and probably until 2020. Figure 1 shows that world refining capacity has been slowly increasing over the last decade. While this trend is expected to continue for at the next 2-4 years, the rate will slow. Throughout the world, it is unlikely that new refineries will be constructed due largely to the economic and legal requirements associated with a new facility. The majority of the increase in capacity will come from upgrades and additions to existing facilities. The Department of Energy projects that distillation capacity in the U.S. will grow from 15.4 million barrels per day (MMB/d) in 1996 to 17.0 MMB/d in 2020 in the low economic growth case and 18.5 MMB/d in the high economic growth case.[7] Note that the U.S. refining capacity was at a peak in 1981 with 18.6 MMB/d. Refinery utilization rates are expected to remain between 93 and 96% throughout this time.

In a recently published survey of U.S. refinery managers,[8] it was reported that:

> "...25% of the respondents indicated no changes to future crude processing capacity, none of the refiners responding to the survey indicated plans to decrease capacity. Most of the other 75% of the refiners planning on increasing crude processing capacity, plan to do so with well-planned refinery revamps at minimal capital investment..."

Additionally, all "of the small refiners and 50% of all the large refiners (>100,000 bbl/d) expressed concerns that there was a 'significant' threat their facility would close in the next 5 years." Reasons for these concerns included shrinking margins and insufficient capital for required upgrades to meet new clean fuel regulations.

In that same refinery managers survey, all the refiners reported their expectation that the worldwide market for diesel fuel (primarily for automotive use) will continue to grow. Some of the larger refiners reported plans to increase their investment in producing middle distillates by over 25%. However, most of the respondents reported more modest investment increases of 5 to 25% for production of middle distillate fuels. The refiners also reported plans to spend from $10 million to as much as $250 million on investments to meet stationary source emissions and meeting clean fuel requirements.

All indications are that the worldwide availability of middle distillate fuels will continue to increase over the next decade. In general, the quality of middle distillate fuels should improve as refinery upgrades come on line and total sulfur levels are reduced. The one notable exception to this trend of general improvement is diesel fuel lubricity. It is expected that as fuels are more and more highly refined, the general trend will be toward poorer fuel lubricity. As shown in Table 2, the refining industry faces various issues, depending on the region of the world. The following section contains brief discussions of selected countries (or regions) throughout the world.

Table 2. Refining Industry Regional Issues[9]

Region	Important Product	Issues
North America	Gasoline	Industry Consolidations
Asia/Pacific	Distillate	Demand Growth and Financial Scrutiny
Western Europe	Distillate	Industry Consolidations
Latin/South America	Gasoline	Bringing Together Production and Refining
Middle East	Distillate	Bringing Together Production and Refining
FSU/Eastern Europe	Distillate	Upgrading Facilities
Africa	Distillate	Project Specific

1. North America

The refining industry in North America is the most mature and sophisticated in the world. There is no other region of the world that is better prepared to process low quality crude oil. As shown earlier, U.S. refinery utilization rates have climbed from about 66% in 1981-1982 to just over 97% in 1997. Most reports put the maximum sustainable utilization rate at about 95%. This high utilization combined with demand growth and expected slowdowns in investments means that the relative amount of imported refined-products will likely increase over the next several years. These increased imports are expected to come from Western Europe and South America.

2. Asia/Pacific

The Asia/Pacific region is arguably the region of the world with the fastest growing demand. This assertion is tempered somewhat by the economic problems in that region at this writing. Approximately 60% of the world's population is in this region and growing affluence will bring increased demand for petroleum. It is projected that this region will surpass North America as the world's leading energy consumer early in the next century. For this reason, the primary thrust of the refining industry in this region is construction of new refineries to meet this expected demand increase. The current economic downturn has slowed the demand some and will likely result in the closing of some smaller or older refineries as new capacity comes online.

National environmental standards in this region vary widely. In general, the degree of severity of the petroleum-related standards is related to the income levels of the country. Japan is the leader in the region, followed by Australia and New Zealand. China and India are at the bottom of the list.[10]

3. Western Europe

As shown in Table 2, the refining industry in Western Europe is, like that in North America, in a period of refinery capacity consolidation. Consolidations brought about by narrow margins and excess capacity. The large majority of upcoming capital expenditures in this region are on upgrades to meet regulatory requirements.

4. Turkey

The state-owned company Tupras, which has four main refining complexes, dominates refining and other downstream operations in Turkey: Batman in the southeast, Aliaga near Izmir, Izmit near Istanbul, and the Central Anatolian Refinery at Kirikkale near Ankara. Tupras has a well-advanced modernization program designed to switch output at these refineries towards light products in line with changing demand. Turkey's sole private refinery is the Association of Turkish and American Scientists (ATAS), near Mersin on the Mediterranean coast, a joint venture of Mobil (51%), Shell (27%), British Petroleum (17%), and local company Marmara Petrol ve Rafineri Isleri AS (5%).[11]

5. Latin/South America

This region is attracting increasing amounts of investment as financial and political problems subside. In general, the individual governments have begun to emphasize clean transportation fuels. Latin America is also expected to be an ever-increasing exporter of refined products to North American markets.

a. Venezuela

Petroleos de Venezuela, S. A. (PdVSA), the state oil company, is the world's fourth largest oil refiner, with a combined domestic and international capacity of 2.4 MMB/d. After opening Venezuela's downstream sector to private investment in 1989, PdVSA began a 6-year, $2.8-billion, domestic refinery upgrade program aimed primarily at increasing the output of light products, such as gasoline, and at meeting environmental restrictions imposed by the 1990 U.S. Clean Air Act. In recent years, Lagoven's 571,000-bbl/d Amuay refinery and Maraven's 286,000-bbl/d Punta Cardon refinery have been upgraded. At Amuay, roughly $630 million has been invested in a 34,000 bbl/d delayed coker, which will reduce the refinery's proportion of residual fuel output. At Punta Cardon, Maraven spent around $2.1 billion to add a 48,000 bbl/d hydrotreater, a 60,000 bbl/d delayed coker, a 60,000 bbl/d reformer, and a sulfur recovery unit using Shell technology. The upgrading at Punta Cardon was intended to create a more favorable product mix, comprising 90% distillates and 10% fuel oil, as compared to the previous output of 70% distillates and 30% residuals.[12]

b. Mexico

According to a 1998 report, the refining industry in Mexico is in a three-year investment program to upgrade facilities. The emphasis will be on "upgrades of existing facilities to process more Mayan crude and produce clean transportation fuels."[13]

6. Middle East

The primary importance of this region, to the world energy marketplace, is as an exporter of crude oil and, to a lesser extent, refined products. Exports of refined products, primarily to the Asia/Pacific region, are increasing. The general ability of the refineries in this region to process lower quality crude is below the global average. Crude oil conversion units are being added to address this problem. In addition, refining capacity is projected to increase by 12.6% by 2001-2002.[14] It is likely that political stability will continue to be a concern in this region.

7. Former Soviet Union/Eastern Europe

At the time of this writing, Russia's economy is in serious trouble. Russian oil production peaked at 11.4 million barrels per day (MMB/d) in 1988. Since then, Russian output has declined sharply and Russian companies have reported to the government that further declines could occur. Russian refineries are in need of large capital expenditures to stabilize and modernize their operations. Prior to the country's current economic crisis, the Russian oil industry had anticipated receiving up to $30 billion in foreign investment during the next five years. The drop in world oil prices, however, has made investment in Russia less attractive, and several proposed investments have fallen through. Russian firms have been forced to limit their capital investments, and exploratory drilling and new well completions have fallen. After a reorganization and privatization process begun in 1993, the Russian oil sector now is divided between vertically-integrated companies and a smaller number of regional independent producers. Restrictions on foreign ownership of privatized oil companies have been removed. Russian refinery throughput in 1997 was virtually unchanged from 1996 levels at 3.7 MMB/d, far below the 38 refineries' rated capacity of 6.9 MMB/d. Many Russian refineries are relatively unsophisticated, oriented towards heavier products, and operating well below capacity. Crude oil is delivered to refineries based upon sulfur content. Low-sulfur oil (less than 0.6% sulfur) is processed by eastern refineries and to the Krasnodar, Tuapse, and Volgograd refineries. Refineries in Novo-Ufa, Ufa, Ufa Neftekhim, Nizhnekamsk, Salavat, and Orsk process the oil with sulfur content exceeding 1.8%. The remaining oil (0.6%-1.8% sulfur content) is processed by refineries close to the producing fields, although blended oil in this sulfur range is also processed by the central refineries such as Moscow, Ryazan, and Yaroslaval. Several refineries have undergone modernization programs. The Yaroslaval 359,000-bbl/d refinery is undergoing a $416 million upgrade by 2002, and NORSI-Oil is undergoing a $350 million upgrade on its 438,000-bbl/d refinery by 2005. Russia's refined product exports in 1997 to countries outside

of the Commonwealth of Independent States (CIS) totaled 1.2 MMB/d, about one-third of total Russian oil exports, and went primarily to Western Europe. Almost all of these exports consisted of diesel fuel and mazut (fuel oil). Product exports to other CIS countries were 70,000 bbl/d in 1997. Product exports have been encouraged by several factors, including: 1) a lack of crude oil export pipeline capacity, 2) a need to generate hard currency, 3) a reduction in rail tariffs to ship products, and 4) the elimination of export tariffs for products.[15]

8. Africa

a. Egypt

Egypt has 8 refineries that can process more than 546,000 bbl/d of crude, with the largest refinery being the 141,000-bbl/d Mostorod refinery outside of Cairo. The government has plans to increase production of lighter products, petrochemicals, and higher-octane gasoline by expanding and upgrading existing facilities. In addition, Egypt's Ministry of Petroleum plans to build 5 new refineries and petrochemical plants valued at $2.5 billion. Egypt's refinery expansion plans include construction of a 35,000-bbl/d hydrocracker at the El-Nasr Petroleum Company refinery in Suez. Also planned is a doubling of capacity at the refinery in Assyut to 100,000 bbl/d. In September 1997, a $33 million management contract was awarded to U.K.-based Kvaerner John Brown for the El-Nasr hydrocracker project, which is expected to cost $450 million.[16]

b. South Africa

South Africa has a highly developed synthetic fuels industry, which takes advantage of the country's abundant coal resources and offshore natural gas and condensate production. The two major players are Sasol (coal-to-oil/chemicals) and Mossgas (natural gas-to-petroleum products). Sasol has the capacity to produce 150,000 bbl/d, and Mossgas 45,000 bbl/d. South Africa is one of the major refining nations in Africa. Its refined products are both sold in the local market and exported, mainly to East Africa, but also into both the Indian and Atlantic markets. Multinational companies (including BP, Shell, Caltex, and Total) are major participants in South Africa's downstream petroleum markets. Although South Africa's refineries generally process Iranian and Kuwaiti crude oil, they all have the flexibility to process different crude oil grades and in recent years have processed oil from Egypt, the North Sea (Brent) and Saudi Arabia. Product from the refineries is transferred to marketing companies based on a basket of refined products in Singapore and the Middle East. As a result, refinery margins tend to follow those in the Far East. All of South

Africa's refineries were built on grass-root sites well away from urban areas. However, over time, population centers have spread to the point where the refineries are now surrounded by habitation. Although the refineries have all spent significant sums in recent years to reduce emissions, the issue of refinery pollution has become a popular one with the fledgling environmental groups in South Africa. South Africa's total refining capacity (excluding synfuel plants) is currently 468,547 bbl/d. The Sasol/Total joint venture announced in November 1998 that it will undertake a $186 million capacity expansion project at its Natref refinery. The project will increase refining capacity at Natref by more than 30%, and include the ability to produce low-sulfur diesel.[17]

C. Refinery Questionnaire

As a means of obtaining additional information concerning petroleum refining and marine fuels production in the future, survey questionnaires were circulated to 45 refineries/oil companies around the world. In selecting recipients for the questionnaires, emphasis was placed on companies that have sold marine fuel (F-76) to the U.S. Defense Logistics Agency (DLA). The refining technology questionnaire is found in Appendix B. Of the 45 questionnaires distributed, 26 were returned. Of those 26, 7 declined to participate, leaving a total of 19 completed questionnaires. Countries from which the completed questionnaires were received include the United States, United Arab Emirates, Japan, Kenya, Argentina, Kuwait, Greece, Pakistan, Brazil, Turkey, Mexico, Chile, and Argentina. A summary of the responses is presented here.

As stated earlier, the objective of this questionnaire was to obtain additional information with which to assess the potential changes in future petroleum-refining technology. The results of the survey questionnaire were also used to estimate changes in the properties of future, commercial, distillate marine fuels and F-76 worldwide, forecast over the next 10 to 12 years. The following is a listing of questions and summarized responses.[18] As expected, the responses were varied and reflect the numerous influences on the person(s) who completed the questionnaires. In fact, some of the responses could be considered in direct contradiction to the generally accepted view on a given question. The responses that were considered most important are underlined for emphasis.

1. Part I - Crudes/Feedstocks

1.) *Please fill in the table below for the types and sources of current crudes or feedstocks the facility receives to refine products.*

Name of Crude/Feedstock	Crude/Feedstock Type (Please indicate Naphthenic, Aromatic, or Paraffinic; Sweet, or Sour: Heavy, or Light)	Volume (bbls) & Percent of Total Feed	Geographic/Company Source

- In total, the responses included Middle East/Asian, African, Mexican, North American, South American, and North Sea crude oils.
- The mix of crude properties was correspondingly varied.

2.) *Do you expect your crude/feedstock slate to change over the next 10 years? If so, how and why?*

- The major portion of the respondents indicated they expected no changes.
- Two responses indicated:
  - High sulfur crude will be the major change due to the price advantage.
  - They expect the trend for lighter/sweeter feedstock purchases & availability to continue.

3.) *Do you expect any of the above crude/feedstock changes to affect your middle/marine distillate fuel production properties? If so, how?*

- The predominant answer was no, there would be little change in feed stock.

Additionally:

- There would be no appreciable change in middle distillates even if the feedstocks change.
- Crudes are expected to be lighter/sweeter.
- Marine gas oil will get closer to ISO standards.

2. Part II - Refinery Products

1.) *Please fill in the table below with the various middle/marine distillate fuels currently being produced at your refinery/facility (i.e. heating oil, automotive diesel, marine gas oil, jet fuel, etc.). Please indicate the relative portion of these products (by percent or volume) to your total production. Identify them by product name/grade and the national, international or company specifications to which they are produced.*

Example responses are listed in the table below.

Product Name/Grade	Specification	Volume Produced (bbl/year)	Percent of Total Production
JP-8/NATO F-34 NATO F-76 Marine Gas Oil – DMA Fuel Oil 180 cSt Fuel Oil 380 cSt JET Auto Diesel/Gas Oil Diesel Gas Oil Jet A-1 Diesel Jet A JP-5	MIL-T-83133 MIL-F-16884 ISO 8217 ISO 8217 ISO 8217 DERD - 2494 ADNOC BS EN 590 BS 2869 Part 2 ASTM D 1655 ASTM D 975 ASTM D 1655 MIL-T-5624	These results were too varied to summarize.	These results were too varied to summarize.

2.) *For the fuels listed above please provide a copy of the specifications indicated if they are other than ISO or ASTM standard specifications. Automotive / marine distillate fuel specifications would be of particular value. We are not seeking company proprietary information, but rather the criteria that the fuels must pass to be sold under the stated specification.*

Some non-ASTM and non-ISO specifications were reported. Typically, copies of those specifications were provided upon request.

3.) *Please fill in the table below with typical inspection data for the fuels listed above.*

1. List inspection data property names in left-most column.
2. List product names/grades across top row.
3. Indicate typical data values in cells

(Example Table)

Property Name	**Product Name/Grade**
Typical Data Value	*Typical Data Value*

The responses to this question were too varied to summarize for this report.

4.) Do you expect your product slate to change over the next 10 years? If so, how may it change and why?

- Ten reported they expect no change.

Other responses:

- Yes, due to growth in capacity with increased naphtha, Jet A-1 & gas oil.
- Yes, expect product slates to get lighter.
- Yes, by increasing conversion unit capacities, more cokers, etc.
- Properties will change due to environmental regulations.

5.) Do you expect any properties of the middle/marine distillate fuels listed above to change in any significant way over the next 10 years. If so, how may they change and why?

Almost all respondents agreed that there will be property changes due to the following reasons:

- Sulfur levels will be reduced (major response).
- Slight decreases will be observed in cetane index.
- <u>Increased environmental legislation will require lower sulfur and additional higher cetane and imposition of aromatic content limits.</u>

6.) Do you expect the unit price of any of the middle/marine distillate fuel oils listed above to change over the next 10 years? If so, how and why?

Responses varied:

- Not possible to predict.
- Not much change.
- <u>Prices will change dependent upon capital investment requirements for lower sulfur, increases in prices of crude oil and government policy.</u>

7.) Do you presently, or would you be willing to produce middle/marine distillate fuel to meet either the U.S. Military Specification, Fuel, Naval Distillate, MIL-F-16884J (NATO F-76), or the U.S. Navy Marine Gas Oil Purchase Description (MGO PD)?
(The fuel property requirements are summarized in the table below.)

- Only 3 respondents answered categorically no.

Most other respondents answered yes with provisos such as:

- <u>It would require long term commitment.</u>
- <u>The cost/profit ratio would have to be viable.</u>
- <u>Only when product requirements meet ISO specifications.</u>

Summary of Fuel Property Requirements for MIL-F-16884J and MGO PD			
Fuel Property	**ASTM Test Method**	**MIL-F-16884J Requirements**	**MGO PD Requirements**
Acid Number, mg KOH/100 ml	D 974 D 664	0.30 (max)	-
Aniline Point, °C	D 611	60 (min)	-
Appearance [1] @ 25°C or ambient, whichever is higher	D 4176	Clear & Bright	Clear & Bright
Ash, wt.%	D 482	0.005 (max)	0.01 (max)
Carbon Residue on 10% Btms, wt%[2]	D 524, D 4530 D 189	0.20 (max)	0.35 (max)
Cloud Point, °C	D 2500	-1 (max)	-1.1 (max)
Color	D 1500	3 (max)	3 (max)
Copper Corrosion @ 100°C	D 130	1 (max)	3 (max)
Distillation, 90% Point°C End Point, °C Residue & Loss, vol %	D 86	357 (max) 385 (max) 3.0 (max)	357 (max) - -
Demulsification @ 25°C, minutes	D 1401	10 (max)	-
Density @ 15°C, kg/m^3	D 1298 D 287 D 4052	876 (max)	876 (max)
Flash Point, °C	D 93	60 (min)	60 (min)
Hydrogen Content, wt %	D 4808	12.5 (min)	-
Ignition Quality, Cetane Number Cetane Index	D 613 D 976	42 (min) 43 (min)	42 (min) 43 (min)
Particulate Contamination, mg/L	D 5452	10 (max)	-
Pour Point, °C	D 97	-6 (max)	-
Sulfur Content, wt %	D 4294 D 129 D 1553 D 2622	1.0 (max)	1.0 (max)
Storage Stability, mg/100 ml	D 5304 D 2274[3]	1.5 (max)	-
Trace Metals, Vanadium, ppm Sodium + Potassium, ppm Calcium, ppm Lead, ppm	D 3605	 0.5 (max) 1.0 (max) 1.0 (max) 0.5 (max)	 - - - -
Viscosity @ 40°C, mm^2/sec	D 445	1.7 - 4.3	1.7 - 4.5
Water and Sediment, vol %	D 2709	0.05 (max)	0.05 (max)

1 Fuels are considered to pass the appearance requirement with a rating other than "Clear and Bright" if they meet both the Water and Sediment requirement and the particulate Contamination requirement.

2 When the finished fuel contains cetane improver, the carbon residue requirement specified shall apply to the base fuel without the cetane improver.

3 ASTM D 2274 may be used as an alternate method for testing storage stability provided the test time is extended from 16 hours to 40 hours.

3. Part III - Processing Treatments

1.) *Please fill in the table below with the various refining processes (i.e. atmospheric distillation, catalytic cracking, hydrotreating, etc) currently used at your facility to make the products listed in Part II above indicating the approximate percentage of each product's total volume derived from each treatment.*

1. List all processes used in left-most column.
2. List all product names/grades across top row.
3. Indicate percentage of each product made by each process

(This is an Example Table for use by the Survey Respondent)

Processing Treatments	Product Name/Grade				
	Marine Gas Oil	*#2 Diesel*			
Atmospheric	*65%*	*85%*			
Hydrocracking	*35%*	*15%*			
Processing Treatments	Product Name/Grade				

The responses to this question were too varied to summarize for this report.

2.) *Do you expect the current mix of processes used in both your refinery and in the refining industry overall to change over the next 10 years? If so how may it change and why?*

Respondents confirmed they expected change as follows:

- Yes, due to environmental concerns for lowering of sulfur, benzene & aromatics.
- Cracking, visbreaking, hydrotreating / hydrocracking will all increase.
- Consequent increases in conversion from residual fuels to distillates.

3.) *Are you aware of any emerging refining processes that could affect the properties of middle/marine distillate fuels produced by you or the refining industry overall? If yes, please describe. Also, please indicate whether your company is likely to implement such processes.*

- The majority of respondents said no.
- One responded with bio-desulfurization.

4. Part IV - Fuel Additives

1.) *If your refinery/facility uses additives to improve the middle/marine distillate fuels produced, please indicate in the table below the additive trade names and chemical composition if known and check off the product name/grade in which they are used.*

1. List product names/grades
2. Fill in additive trade names and chemical compositions in appropriate cell for the additive type.
3. Check off the appropriate box for the product containing the additive.

(This is an Example Table for use by the Survey Respondent)

Additive	*Additive Trade*	*Additive Chemical*	*Product Names/Grade*		
			M G O	*#2 Diesel*	
Cetane		*Amyl-nitrate*		*Y*	
Storage Stability Improver	*Dupont, FOA-3*		*Y*		

Additive Classes	Additive Trade Name	Additive Chemical Composition	Product Names/Grades		
Cetane Improver					
Cold Flow Improver					
Detergent / Dispersant					
Lubricity Improver					
Storage Stability Improver					
Thermal Stability Improver					
Others (Specify)					

Respondents answered with specific additive packages they use which were predominately:

- Cetane improvers.
- Cold flow improvers.
- Storage stability improvers.
- Lubricity improvers.
- Static dissipator additives.
- Thermal stability improvers.

2.) Do you expect the use of additives both in your products and in the refining industry overall to change over the next ten years? If so, how may it change and why?

- Six reported they expected no change.
- The remaining respondents answered yes:
  - Changes required for greater use of cetane & lubricity improvers.
  - Yes, dependent upon the improvements in diesel-engine technology.
  - Regulatory requirements may dictate an increase in use.

5. Part V - Environmental Regulation Impact

1.) What current or future environmental regulations (international, national, regional, etc.), applicable to refinery operation/technology affect or may affect your production of middle/marine distillate fuels?

- Regulations to reduce sulfur caps in gas oil to 50 ppm.
- Air regulations, SO_2, NO_X, particulates and ground water regulations, which will increase operational costs.
- Government regulations to reduce smog/ozone which will force need to install de-aromatic facilities and necessitate changes in operational modes.
- EPA low-sulfur diesel regulations, Internal Revenue Service dye regulations, state home-heating oil sulfur regulations.
- NO_X reduction regulations may limit crude runs or desulfurization capacity.

2.) What current or future environmental regulations (international, national, regional, etc.) are applicable to the middle/marine distillate fuels you produce?

- Four answered 'none presently.'
- The majority advised of anticipated government regulations for sulfur limits, PM_{10} (mass fraction of particles with aerodynamic diameters less than 10μm) emissions, NO_X emissions.

- A few advised of limits in effect presently.

3.) *Are current environmental regulations responsible for any significant changes in the properties of the middle/marine distillate fuels? If yes, please explain.*

- Eight respondents said no.

The remaining respondents reported that the affected fuel properties were:

- Sulfur, cetane numbers, final boiling point, aromatic content, lower lubricity, and dyes.

4.) *Is there any governmental air quality standard(s), either current or future, which affect your company's ability to produce, or your customer's ability to use middle/marine distillate fuels? If yes, please describe.*

- Seven respondents said no.
- One respondent said current NO_X reductions may limit crude runs on desulfurization capacity.
- One said government air quality standards to reduce NO_X & SO_X will affect production.

5.) *What directions or trends do you foresee for the next 10 years in environmental regulations regarding refinery operations, middle/marine distillate fuel composition, and engine emissions?*

The majority of respondents cited the following trends regarding refinery operations:

- Zero flare operations.
- Lower sulfur and lower aromatics.
- Lower benzene and olefins in gasoline.
- Allowable engine emissions are slated to drop significantly in 2004.
- PM10 & NO_X reductions in diesel for light & heavy duty engines.
- ISO 14000 is the only anticipated regulation under evaluation.

6.) *Is the demand for better-quality middle/marine, distillate fuel increasing? What do you see as the trend for the next ten years?*

The majority stated that the demand for better fuel quality is increasing due to:

- More stringent emissions requirements.
- Higher horsepower and improved engine designs.
- Two respondents said no increase.

7.) *In the last ten years, have you been required to lower the total sulfur content of your middle/marine distillate fuels by either regulatory agencies or customer requirements? If yes, please describe those requirements.*

- Ten respondents said yes.
- Five respondents said no.

8.) *Some environmental regulators around the world are advocating total sulfur limits of 50 ppm for middle distillate and diesel fuels by the year 2005. Is your company, or would your company be willing to undergo changes in your refining processes to meet this sulfur level? Would reduced sulfur limits have any impact on fuel production?*

- One company said they would not invest -- the cost would be 1 billion dollars and 'yes' it would impact production.
- Most other respondents said they would invest but the costs would be extensive, there would be significant financial impact and it would impact production.
- Some said economic analysis would be required first and that these changes would only be made if the market place supported this.

A summary of the responses follows:

- Feedstocks haven't changed much in past and are not likely to change much in near future.
- Refineries were committing to additional refining capacity.
- Some respondents were prepared to produce fuel to meet military specifications if long-term government commitments could be obtained.
- Increased conversion capacity would reduce availability of residual products.
- Middle distillate product prices may not continue to be directly related to crude prices if environmental trends force large investments.
- Additional investments are being made to increase hydrotreating/hydrocracking and coking processes.
- Additive usage may increase as better quality fuel is demanded.
- Additives are used to enhance combustion, reduce soot formation, keep engines clean, control emissions, improve lubricity, and reduce biological degradation.
- Reductions in sulfur content, aromatic content, benzene & olefins will be the primary property issues.

VI. FUEL QUALITY

A. 1983 to Present

Over the past 10 to 15 years, the quality of distillate marine fuels around the world has undergone significant change. Some of the reasons for this were discussed in the previous section. These changes include things such as new environmental legislation, the refining industry, and crude oil slates. The general opinion is that the quality of marine fuel has improved, with some exceptions.

In an effort to ascertain and track the quality of available marine fuels, fuel surveys were conducted in 1983, 1986, and 1996. A summary of the findings from these surveys follows.

1. 1983 Survey

In 1983, 50 samples of commercial marine fuels were obtained from various ports around the world and were analyzed.[19] The fuels included 20 marine gas oils (MGO's), 10 heavy marine gas oils (HMGO's), 7 marine diesel fuels (MDF's) and 13 intermediate fuel oils (IFO's). These were define as:

- MGO—100% distillate transported in dedicated equipment to prevent contamination.
- HMGO—100% distillate without transportation requirements (may result in up to 0.5 vol.% contamination by residual fuel).
- MDF—distillate blended with up to 10 vol.% residual.
- IFO—residual fuel and distillate blended to specified viscosities.

The samples were obtained from a wide distribution of ports around the world. Although single random fuel samples may not accurately represent a refinery product, it was possible to draw some general conclusions regarding the possible Navy use of commercial marine fuel products. The results indicated that the quality of the fuel samples varied over a wide range within each fuel grade. Also, the supplier might have more appropriately classified some of the fuel samples. No attempt was made to reclassify fuels based on analytical results.

The fuel analysis results were compared with the requirements of the Navy fuel specification then in use, MIL-F-16884H. For the purpose of this report, we will consider only the 20 fuels

identified as marine gas oil. Table 3 is a compilation of the number of fuels that failed to meet the specification requirements for several common fuel properties.

Table 3. MIL-F-16884H Fuel Property Failures – 20 MGO Samples from 1983			
Fuel Property	**Test Method**	**Limits**	**Number of Failures**
Cloud Point, °C	D 2500	-1, max	13
Pour Point, °C	D 97	-6, max	8
Viscosity, centistokes, @ 40°C	D 445	1.7 - 6.0	7
Ash, percent	D 482	0.005, max	6
Storage Stability, total insol, mg/100 mL	D 2274	1.5, max	4
Distillation, final boiling point, °C	D 86	385, max	2
Acid Number	D 974	0.30, max	1
Copper Corrosion @ 100°C	D 130	No. 1 ASTM, max	1
Water & Sediment, vol percent	D 2709	0.01, max	1
Demulsification, minutes, @ 25°C	D 1401	10, max	0
Color	D 1500	3, max	0
Appearance	---	Clear & Bright	0
Total Sulfur, percent	D 129	1.00, max	0
Cetane Number	D 613	45, min	0
Flash Point, °C	D 93	60, min	0

The highest number of failures in the samples collected occurred with cloud point, pour point, viscosity, and ash.

2. 1986 Survey

In 1986, the Navy implemented a second survey of commercial marine fuels with emphasis placed on MGO's and HMGO's.[20] Samples of MDF were collected from ports where samples had been previously obtained. No IFO's, or similar heavy fuels, were sampled unless it became known that a particular IFO was being used as a blending stock with MGO's to deliberately produce HMGO's. In addition, emphasis was placed on surveying commercial marine fuels in the Middle East, Far East, and South America, a recommendation from the previous survey.

As in 1983, 50 samples were obtained from suppliers in ports geographically spread around the world. Some of the suppliers and samples were chosen for the 1986 survey because they echoed the samples taken in the first survey. This was done to assess trends in fuel quality. Other suppliers and ports were chosen to gain a better geographical representation.

All three grades of fuels were analyzed and the results were reviewed for (1) compliance with the refinery/product specifications; (2) compliance with the then current F-76 specification requirements; and (3) comparison of results obtained from the 1983 survey.

a. Marine Gas Oil

Refinery--in comparing the analytical results of the MGO samples to their respective refinery specifications, it was recognized that all of the samples were in general compliance with specification requirements. The greatest number of specification failures occurred in the requirement of a clear and bright appearance; 4 of the 15 samples analyzed failed. These failures were due to the appearance of particulate matter in the fuel samples.

Comparison of MGO to F-76--The fuel properties which most often failed were appearance and cloud point. Of the 15 MGO samples analyzed, all 15 failed the appearance requirement of "clear and bright." Again, this was largely due to the appearance of particulate matter within the fuels. Nine of the samples fell outside the pour point and 90% distillation point specification. The majority of the MGO samples met the remaining F-76 requirements.

Comparison with 1983 Survey--The results were quite similar to those obtained from the 1983 survey. As in the 1983 survey, a great number of the MGO's failed the F-76 cloud point and pour point requirements. None of the MGO's in the 1986 survey failed the carbon residue or ash requirement. In all, the results obtained on MGO's from both of the surveys indicate a general compliance with the F-76 specification for this grade of fuel.

b. Heavy Marine Gas Oils

Refinery--As the survey progressed, it was noted that a large number of suppliers did not market a fuel corresponding to the HMGO definition. Of the HMGO samples that were collected and analyzed, all were within their respective refinery specifications. While the largest number of failures for the MGO's occurred in the appearance requirement, no such requirement was specified for any of the HMGO's.

Comparison of HMGO to F-76--Properties for which a large number of MGO's failed the F-76 specification were also failed by most of the HMGO's. Other properties that were frequently outside the specification requirements were distillation, end point and residue plus loss,

viscosity, carbon residue on 10% bottoms, and color. As with the MGO's, all HMGO's failed the appearance criteria due to particulate matter in the samples. All four HMGO samples also failed the cloud point and color requirements. The color in some instances was so dark that even after following the dilution procedure, as outlined in ASTM D 1500, the color was still reported as "8 dil" (diluted). Three of the four HMGO's failed in the following areas: distillation requirements of 90% point, end point and residue plus loss, pour point, viscosity, carbon residue on 10% bottoms, and demulsification.

Comparison with 1983 Survey--Though results on only four HMGO's were available from the 1986 survey, there appear to be some major differences in comparison with results of the 1983 survey. The boiling range of the HMGO's from the 1986 survey is narrower. The median cloud point is lower. The range of cloud and pour point temperatures was less: 0 to 12 °C versus -2 to 30 °C for cloud point; and, -6 to 9 °C versus -46 to 27 °C for pour point. These changes are probably largely due to lack of proper classification of fuel samples in the 1983 survey. In addition, analytical information is available on only four HMGO's from the 1986 survey.

A notable difference was also observed in the sulfur level of the fuels. The median sulfur level of HMGO's as analyzed in the 1986 survey was 0.64 wt% while in the 1983 survey the median was 0.32 wt%. The highest sulfur levels reported were 1.49 and 1.02 wt% in the 1986 and 1983 surveys, respectively.

3. 1996 Survey

The 1986 survey sought samples of Marine Gas Oil, Heavy Marine Gas Oil and Marine Diesel Fuel. The 1996 survey[21] was limited to samples of Marine Gas Oil (MGO) and Ground Vehicle Diesel Fuel (GVDF). The following definitions were used to identify MGO and GVDF fuels sampled:

> Marine Gas Oil—a middle distillate fuel which contains no residual fuel (i.e. 100% distillate) or dyes, is produced from petroleum crude, and has a minimum flash point of 60°C as measured by ASTM D 93 or equivalent method. It is typically intended for use in off-highway and marine diesel engines.

Ground Vehicle Diesel Fuel (GVDF)—a middle distillate containing no residual fuel (i.e. 100 distillate) or dyes and produced from petroleum crude. It is typically intended for use in ground vehicles and equipment powered by diesel engines. This fuel is similar to Grade Number 2D of ASTM specification D 975. It is also similar to U.S. Defense Logistics Agency Commercial Item Description AA-52557 which has replaced DF-2 of former Federal Specification VV-F-800D. However, for the purpose of this survey, it is not limited by these specifications.

A total of forty-two samples were obtained and analyzed.

Comparison with MIL-F-16884J--Only three of the forty-two samples passed all requirements of Military Specification MIL-F-16884J. The fuels that passed were obtained from refineries in Panama, Alaska, and Northern California. Of the remaining 39 samples, nine failed only one specification requirement (either acid number, cetane number/index, cloud point, color, distillation residue plus loss, particulate contamination, or pour point). Seven failed two specification requirements (such as ash, cloud point, color, distillation residue plus loss, particulate contamination, or pour point) and twenty-three failed three or more specification requirements (such as aniline point, cloud point, color, distillation end point, particulate contamination, pour point or storage stability). Table 4 shows the number of fuel samples that failed each of the required MIL-F-16884J fuel properties ranked in order of most failures to the least failures.

Table 4. Failure Ranking of MGO Properties Relative to MIL-F-16884J and MGO PD

Property	Test Method Number	MIL-F-16884J		MGO PD	
		Limits	Failures	Limits	Failures
Pour Point, °C	D 97	-6 (max)	22		
Particulate Contam., mg/L	D 5452	10 (max)	18		
Cloud Point, °C	D 2500	-1 (max)	13	-1.1 (max)	13
Color	D 1500	3 (max)	10	3 (max)	10
Aniline Point, °C	D 611	60 (min)	8		
Distillation 90% Point, °C	D 86	357 (max)	3	357 (max)	3
Distill. Residue + Loss, vol%	D 86	3.0 (max)	8		
Distillation End Point, °C	D 86	385 (max)	7		
Storage Stability, mg/100 ml	D 5304	1.5 (max)	6		
Viscosity @ 40°C, mm^2/sec.	D 445	1.7 – 4.3	6	1.7 – 4.5	4
Ash, wt.%	D 482	0.005 (max)	5	0.01 (max)	1
Carbon Residue on 10% Btms, wt%	D 524, D 4530	0.20 (max)	5	0.35 (max)	3
Ignition Quality					
Cetane No.	D 613	42 (min)	5	42 (min)	5
Cetane Index	D 976	43 (min)	5	43 (min)	5

Table 4. Failure Ranking of MGO Properties Relative to MIL-F-16884J and MGO PD					
Acid Number, mg KOH/g sample	D 974	0.30 (max)	3		
Hydrogen Content, wt.%	D 4808	12.5 (min)	3		
Demulsification, minutes	D 1401	10 (max)	2		
Flash Point, °C	D 93	60 (min)	2	60 (min)	2
Appearance (1)	D 4176	C&B	0	C&B	0
Copper Corrosion	D 130	1 (max)	0	3 (max)	0
Density @ 15.6°C, Kg/M^3	D 1298, D 4052	876 (max)	0	876 (max)	0
Sulfur content, wt.%	D 4294	1.0 (max)	0	1.0 (max)	0
Trace Metals					
V ppm	D 3605	0.5 (max)	0		
Na + K ppm		1.0 (max)	0		
Ca ppm		1.0 (max)	0		
Pb ppm		0.5 (max)	1		
Water and Sediment, vol.%	D 2709	0.05 (max)	0	0.05 (max)	0
(1) Fuels were considered to pass the appearance requirement with a rating other than "Clear and Bright" if they met both the Water and Sediment requirement of 0.05 vol.% (max) and the Particulate Contamination requirement of 10 mg/L (max)					

As can be seen in Table 4, the cold flow properties, cloud point and pour point were two of the most restrictive of the specification requirements. The amount by which the fuels failed these requirements varied from one or two degrees above the allowable maximum to 20 degrees above the allowable maximum. Twelve fuels that failed both cloud point and pour point were refined in tropical regions. The remaining nine fuels which failed the cloud point requirement and the remaining three fuels which failed the pour point requirement were refined in temperate regions. Of the eleven fuels refined in the United States, ten passed both of the cold flow property requirements while the fuel from Hawaii failed both cloud point and pour point.

Table 4 also shows that the second most restrictive specification requirement was particulate contamination. Eighteen of the forty-two samples failed the particulate contamination requirement. The particulate contamination results generally followed the overall quality of the fuels. Of the fifteen fuels that failed only one or two specification requirements, only three failed particulate contamination, and two of these three fuels (Chile and England) failed by only one mg/L (11mg/L vs. 10 mg/L maximum). Of the twenty-four fuels that failed three or more specification requirements, only nine passed the particulate contamination requirement. Typically, government contracts for F-76 stipulate that the storage tanks be dedicated to F-76 only to limit contamination. Since this survey concentrated on obtaining samples of typical commercial fuels, the particulate contamination results may reflect the general level of cleanliness in the fuel systems sampled.

Although Table 4 shows that color was the fourth most restrictive fuel property, seven of the ten fuels which failed the color requirement probably did so because they contained dye. One of the items on the questionnaires, which were circulated to the 1996 survey participants, asked whether the fuel sampled contained any dye and what was the dye dosage. While only seven of the forty-two refiners responded that they did add dye to their fuel, six of these dyed fuels failed the F-76 color requirement. The one dyed fuel that passed the F-76 requirement was obtained from the Netherlands. Five of the dyed fuels that failed the F-76 color requirement came from locations in the United States where red dye is required to identify untaxed, off-road fuel. The sixth dyed fuel that failed the F-76 fuel requirement came from Belgium where red dye is used to identify MGO for excise tax purposes.

While the information received for the seventh fuel to fail the F-76 color requirement contained no information regarding dye content, color was the only F-76 requirement that this fuel, obtained from Southern California failed. Since this is an area where red dye use is required for off-road diesel fuels, this failure was believed to be due solely to the presence of red dye, and constituted a false failure. The three other fuels that failed the F-76 color requirement were obtained from scattered locations outside the United States. The questionnaires from two of these fuels (Columbia and Japan) identified them as containing no dye. The questionnaire for the third sample (Spain) provided no information regarding dye content. All three of these fuels failed four or more F-76 requirements, and were not considered to be good quality fuels. The results of the ASTM D 1500 color test were clearly skewed by the presence of dye in some of the samples.

Only one fuel (Djibouti) had any trace metals (0.62 ppm lead) that exceeded the MIL-F-16884J limits. Measurable amounts of the five trace metals mentioned in MIL-F-16884J (calcium, lead, sodium, potassium and vanadium) were found in only eleven of the forty-two samples and all but one were within specification limits. The presence of trace metals, especially lead and vanadium, can promote hot corrosion of gas turbine engine vanes and blades.

<u>Comparison with the Navy's Marine Gas Oil Purchase Description (MGO PD)</u> -- The MGO PD has thirteen fuel property requirements while MIL-F-16884J has twenty-six. In addition to having half as many requirements as MIL-F-16884J, the limits specified in the MGO PD for ash content, carbon residue, viscosity and copper corrosion are less restrictive. Table 4 shows the

fuel properties required in MIL-F-16884J and the MGO PD as well as the property limits for each. Table 4 also shows the number of fuel samples that failed each of the required MGO PD fuel properties.

Nine of the forty-two samples analyzed passed all requirements of the MGO PD. The fuels which passed included the three mentioned above as passing MIL-F-1688J (Panama, Alaska and Northern California) plus six other fuels from refineries in Chile, England, New Zealand, Turkey, Venezuela, and Texas. This represents one-fifth of the total number of samples analyzed. Of the remaining thirty-three samples, seventeen failed only one PD requirement (such as cloud point, cetane number/index, carbon residue on 10% bottoms, and color). Fourteen failed two PD requirements (such as cloud point, cetane number/index, flash point, viscosity @ 40°C, and distillation 90% point) and two failed three or more PD requirements.

The three samples that passed all requirements of MIL-F-16884J not surprisingly also passed all of the requirements of the MGO PD. These three fuels would be considered fully compatible with Navy shipboard fuel combustion and fuel handling equipment.

The other six fuels mentioned above as passing all requirements of the MGO PD contain properties that did not meet MIL-F-16884J requirements and were not addressed by the MGO PD. For these six fuels (Chile, England, New Zealand, Turkey, Venezuela, and Texas), the property deficiencies relative to MIL-F-16884J involved only one or two properties (such as acid number, distillation residue + loss, pour point, and particulate contamination). The Navy's policy of immediately using MGO PD taken aboard (i.e. within 6 weeks) would probably be sufficient to avoid operational problems with these fuels as long as ship operations were confined to relatively warm waters.

There is no fuel storage stability requirement in the MGO PD and as shown in Table 4, there were six samples that failed the storage stability requirement of MIL-F-16884J. Fuel instability has the potential to plug filters and/or fuel injectors and can begin to do so as soon as the fuel is brought aboard. Such problems have occurred infrequently both aboard ship and in fuel storage facilities ashore with fuels which, at the time of procurement, met all requirements of the MGO PD.

Comparison with ASTM D 2069, Grade DMA--The ASTM Standard Specification for Marine Distillate Fuels, D 2069, Grade DMA has 17 fewer requirements than Military Specification MIL-F-16884J and it contains both a summer pour point limit of 0°C and a winter pour point limit of –6°C. Thirty-seven Worldwide Survey sample sites were in their local summer season and five sample sites were in their local winter season at the time the samples were drawn. The ASTM D 2069, Grade DMA summer pour point limit, 0°C, was used for all samples drawn during the local summer season, and the winter pour point limit, -6°C, was used for all samples drawn during the local winter season.

Twenty-four of the 37 samples drawn during the local summer season passed all requirements of ASTM D 2069, Grade DMA. Twelve samples failed only one specification requirement. Of those 12, five failed the maximum summer pour point of 0°C, four failed the maximum carbon residue (on 10% of bottoms) requirement of 0.20 wt%, two failed the minimum cetane number requirement of 40, and one failed the minimum flash point requirement of 60°C. One fuel sample failed both the maximum ash content requirement of 0.01 wt% and the minimum flash point requirement.

Only one of the five samples drawn during the local winter season passed all requirements of ASTM D 2069, Grade DMA. Three samples failed the maximum winter pour point requirement of –6°C. One sample failed the maximum carbon residue requirement of 0.20 wt% and the maximum winter pour point.

The same four samples which passed all requirements of MIL-F-16884J and the MGO PD also passed all of the requirements as ASTM D 2069, Grade DMA. These four fuels would be considered fully compatible with Navy shipboard fuel combustion and fuel handling equipment.

Seven fuel samples which were acceptable under the MGO PD, but not acceptable under MIL-F-16884J, were acceptable under ASTM D 2069, Grade DMA. These fuels included six that were earlier shown to be minimally off-specification and unlikely to cause shipboard operational problems. However, one fuel sample of this group exceeded the MIL-F-16884J limits for ash content, pour point, storage stability and trace lead content. That sample was judged as having the potential to cause significant shipboard operational problems.

Three fuel samples which had been acceptable under the MGO PD were unacceptable under ASTM D 2069, Grade DMA. All three failed the maximum summer pour point requirement of 0°C, which is not tested under the MGO PD.

Fourteen other fuel samples, which were acceptable under ASTM D 2069 Grade DMA, were not acceptable under either MIL-F-16884J or the MGO PD. Under the stricter MIL-F-16884J these fuels had failed from two to six property requirements. Seven fuels of this group had property deficiencies relative to MIL-F-16884J that were relatively minor and were unlikely to cause significant shipboard operating problems, especially if consumed promptly after receipt. However, seven other fuels of this group had serious property deficiencies relative to MIL-F-16884J and were virtually certain to cause significant shipboard operating problems.

4. Navy Fuel Property Database

Additional fuel-quality information is available from a database maintained by the Navy. This database contains the results of laboratory analysis of samples of F-76 purchased for the Navy. Appendix C contains charts of the data from fiscal year 1990 through fiscal year 1998. The data as plotted are a rolling seven-month average. Note that the data are shown as "All Refiners Worldwide," "US Refiners," and "Non-US Refiners." A discussion of selected data follows. The interested reader is directed to ASTM Manual 1 for a discussion of the significance of these fuel properties.[22]

- The acid number data show an increase for the U.S. refiners but relatively no change for the non-US refiners. All results are below the specification limit.
- The ash content data show a gradual decrease for both non-US and US refiners.
- Carbon residue (on 10% bottoms) is decreasing for both non-US and US refiners.
- Cetane index has averaged about 50 over this time period (approximately 48 for US refiners and 52 for non-US refiners). This is well above the limit of 43 minimum.
- The color data show some high values for US refiners.
- The average flash point is decreasing; presumably as the fuels become more highly refined to meet tighter specifications and regulations.
- The average particulate content of F-76 fuels delivered to the Navy is well below the specification maximum limit of 10 mg/L.

- Storage stability results, as measured by ASTM D 5304 and ASTM D 2274, 40 hrs, are improving. This is also thought to be due to increased refining to meet tighter specifications. The data for the standard conditions of ASTM D 2274 are not considered indicative of the stability characteristics of the fuel.
- Average total sulfur content remained relatively unchanged.
- The average trace metals content decreased.
- The average viscosity remained relatively unchanged.

B. Future Fuel Quality

While it is not possible to know the quality of future fuels with absolute certainty, it is possible to make some predictions based on current knowledge, experience, and technical judgement. In general, it is expected that:

- The quality of petroleum fuels, especially gasoline and diesel fuel, will continue to increase over the next ten years.
- The one fuel property that is expected to worsen over the next several years is lubricity.
- Oil companies worldwide will continue investments in both new refineries and upgrades to help them process crudes of decreasing quality yet produce fuels to meet even tighter specifications and requirements.
- With only a few exceptions, national environmental regulations are getting stricter, especially allowable total sulfur levels.

C. Alternative Fuels

As in the early 1980s, research with alternative fuels is again on the increase. Whereas the earlier work centered on the suitability of these fuels to power diesel engines; most of the current work is evaluating the potential these fuels offer to reduce engine emissions.[23] The following fuels are the ones that seem to show up the most in the literature and reports from the government:

- Fischer-Tropsch Liquids
- Biodiesel
- Ethers and Alcohols

- Naphtha
- Gaseous Fuels

Assuming current and near-future technologies and infrastructure, only Fischer-Tropsch liquids can be considered a viable alternative fuel for Navy use, at this time. This is because biodiesel tends to be more sensitive to the presence of water, and the other fuels listed have flash points that are too low for shipboard use. Biodiesel blends (B20) can also have storage stability problems, especially in the presence of copper.[24] Some regulators and researchers consider ultra-low sulfur diesel fuel as an alternative fuel to current diesel fuels. For the purposes of this report, ultra-low sulfur diesel is not considered an alternative fuel.

Fischer-Tropsch Synthesis is the process whereby natural gas is converted into hydrocarbons. The product hydrocarbons are usually upgraded to middle distillate products such as kerosene and diesel fuel. Typically Fischer-Tropsch diesel fuels have high cetane numbers, often greater than 70 cetane, no aromatic compounds, no sulfur, and a density of around 0.78 kg/L[25]. The Fischer-Tropsch liquids have been evaluated as a diesel fuel and as a blend component with conventional petroleum diesel fuel.

Schaberg, et al[26] tested two variations of the Sasol distillate fuels, a 2-D diesel fuel, a CARB (California Air Resources Board) diesel, and three blends of the Sasol fuel with the 2-D fuel. The Sasol fuels produced significantly lower engine emissions than the 2-D and CARB fuels. The fuel blends reduced emissions in proportion to the amount of the Sasol fuel in the blend. Other researchers have shown similar improvements in regulated emissions, with the use of Fischer-Tropsch fuels, as well.[27, 28, 29] The most significant potential problem associated with the use of these fuels is lubricity. Fischer-Tropsch fuels have very poor lubricity properties. There may also be some elastomer/seal swell problems, especially in older fuel systems, since these fuels have no aromatic compounds.

VII. ENGINE TECHNOLOGY

A. History

For the purposes of this project, engine technology referred to both diesel and gas turbine engines. While the primary emphasis is on engines for ship propulsion, engines for auxiliary

applications, such as power generation, were also considered. It is recognized that engines for marine applications can be distinctive from their non-marine counterparts. Emissions requirements are typically less restrictive for marine engines (although this trend is changing). Marine fuel quality is often lower than automotive fuel. Not all of the technology presented in this section of the report is strictly for marine applications. It is assumed, however, that much of the technology originally developed for non-marine applications will be transferred to marine engines where appropriate.

With a few exceptions, gas turbine engines are the predominant engines for propulsion of U.S. Navy surface combatants. Appendix D contains summaries of ship main propulsion and ship-service generator engine types for the Navy.[30] Gas turbine engines are also used in select auxiliary applications. Diesel engines tend to be used primarily for power generation, small ship propulsion, and some shipboard material handling equipment.

Since the late 1930s, the U.S. Navy has had an invested interest in the development and application of marine gas turbines. At that time, initial internal studies were performed into the application of gas turbine engines for shipboard propulsion and power generation. The studies showed that with sufficient funding and development, these engines offered significant advantages over the existing shipboard steam or diesel propulsion systems. The main advantage was the ability to provide a large power to volume ratio, which would provide greater space for weapons or hotel services. In addition, the use of gas turbines offered the potential to reduce maintainability and manning requirements for shipboard engineering plants because of a reduction of required components to provide power.

Throughout the 1940s and 1950s, laboratory testing by the U.S. Naval Engineering Experiment Station, presently known as NSWC Annapolis Md., focused on the improvement of these primitive engines to withstand higher combustion temperatures for longer periods of time. This was needed to provide the necessary power requirement for shipboard use. Significant work was performed to improve engine components and materials, which also resulted in improvements in fuel consumption.

On a small scale, the gas turbine engine was shown to operate at fuel consumption rates comparable to a steam plant. However, to make this system practical for large-scale application, and eventual replacement of the steam plant, further development and testing had to be performed in the lab and in small shipboard applications. Thus, the goal of these tests was not only to increase the scale, but also to improve the efficiency beyond the capability of either the steam or diesel engines being used.

Engines designed and developed specifically for marine use by the Navy were produced for small boat operations and surface ship emergency power. However, as testing progressed, it became apparent that the funding level necessary to develop technology improvements specifically for the large-scale application of shipboard gas turbines was not adequate. The development effort could not match what the commercial and military aircraft industries were already accomplishing. After an analysis was completed comparing both the aircraft and marine efforts, the decision was made to be more cost effective and eliminate the redundant development of technology by applying what these other industries were accomplishing. The technology improvements would be evaluated as entire engines and individual system components. The focus could then be put towards optimizing the engines for marine applications and use by the fleet. Subsequent full-scale testing and modification of these aircraft engines for Navy use was accomplished by the U.S. Naval Ship Engineering Center, presently known as Naval Surface Warfare Center (NSWC), Philadelphia.

By the late 1960s, approximately 90% of U.S. Navy surface combatants were powered by steam plants. In contrast, there were no ships that utilized gas turbines. They were used only in specialized, small-boat applications. The major impediment holding back the Navy from further application of gas turbine engines was the type of fuel burned. The primary propulsion fuel at the time was Navy Special Fuel Oil (NSFO)[31], which was heavier but cheaper than diesel fuel. Because of the poorer quality of the NSFO, it could be burned in steam plants, but not in gas turbines or diesels. The Navy was therefore buying, storing, delivering, and using two different types of fuel. Also, since NSFO was cheaper, the cost of operating a steam plant was less, even though the fuel consumption rates for gas turbines and steam plants were comparable. However, once the Navy decided to change to a single fuel, thereby reducing logistics costs and eliminating the additional cleaning costs associated with the use of NSFO, the cost advantage of operating steam plants disappeared.

Once all of the obstacles for application were eliminated, NSWC Philadelphia, personnel performed full-scale testing and modifications. Both land-based engines and shipboard engines on the GTS Callaghan were involved in efforts to improve the reliability of gas turbine engines. As a result of these efforts, the basic layout of the gas turbine plant was finalized and has been used on all classes of surface combatants ever since. With the advent of the DD963 Destroyer, the decision was made to apply this power plant on a full scale. The power plant consisted of four General Electric LM2500 gas turbines for main propulsion and three Allison 501K series gas turbines for power generation.

By the end of the 1970s, with the application of gas turbine plants and the introduction of new classes of ships including the FFG7, the profile of Navy propulsion was starting to change. At this time, approximately 78% of the surface combatants were still steam plants with 15% being gas turbine. However, this proportion changed in the next 10 years as steam ships were being retired and new gas turbine ships, including the CG47 class, were being built. By the end of the 1980s, this profile changed to 57% being steam-propelled while 40% operated with gas turbine plants.

This trend has continued over the past ten years to the latter part of the 1990s. With the inception of the DDG51 class and further reduction of available steam ships, the Navy surface combatant profile consists of 87% gas turbine plants and approximately 1% steam ships. Of these gas turbine plants, there are 436 LM2500 main propulsion engines, 186 501-K17s and 69 501-K34 gas turbine engines used for Ship Service Gas Turbine Generator Sets presently in service.

Even though the overall performance of the gas turbine plant was proven on the GTS Callaghan and subsequent land based testing, the emphasis of the Navy since the inception of this basic power plant, has been to increase the reliability of the associated systems used by the gas turbine engine. The majority of these systems were directly carried over from aircraft applications and had significant problems when exposed to a marine environment. As a result, a significant amount of work was performed by NSWC Philadelphia, sponsored by the life cycle manager SEA 03Z, to modify these systems to operate in a marine environment. The purpose of this effort was to improve the mean-time-between overhauls and failures. Through NSWC's Design, Development, and Implementation program, over 80 Engineering Change Proposals were

developed and implemented into the fleet on all of the gas turbines. These changes were also incorporated into new shipboard gas turbine designs to ensure that the reliability improvements carried over into the next class of ships. Other programs including Component Improvement Programs, sponsored by SEA 03Z, with original equipment manufacturers, produced further improvements in the gas turbine systems. As a result of these efforts, the mean-time-between failures for the GE LM2500 and the Allison 501K engines were significantly increased.

While the Navy's main emphasis was the adaptation of aviation gas turbine systems for the basic marine gas turbine plant to increase reliability, gas turbine manufacturers have made significant technology developments for commercial and military aircraft and industrial gas turbine users. These improvements centered on the advancement of blade, vane, and combustor materials, control technology, and sealing capability to eliminate losses. NSCW, Annapolis, Code 60, along with the engine manufacturers, were responsible for developing the turbines' hot section blades and vanes base materials and coatings to withstand hot corrosion in a marine environment for the Navy's application of aero-derivative gas turbine engines. In addition, initiatives were made to further streamline inlet and exhaust airflow while modifying the respective temperatures to improve performance. The overall goals of these programs were reduced fuel consumption, increased engine performance output, and reduced emissions.

The interested reader can find additional information on the history of gas turbine engines in the Navy in the cited reference.[32]

B. Engine Technology Questionnaire

Questionnaires were circulated to 22 (17 returned) of the engine companies with engines currently in the Navy, Coast Guard, and Military Sealift Command fleets to obtain additional information concerning engine technology in the future. Figures 4 and 5 are graphical representations of the relative percentages of given engines (size and/or application) by engine manufacturer for the combined Navy, Coast Guard, and Military Sealift Command fleet. The engine technology questionnaire is found in Appendix E. A summary of the responses is presented here.

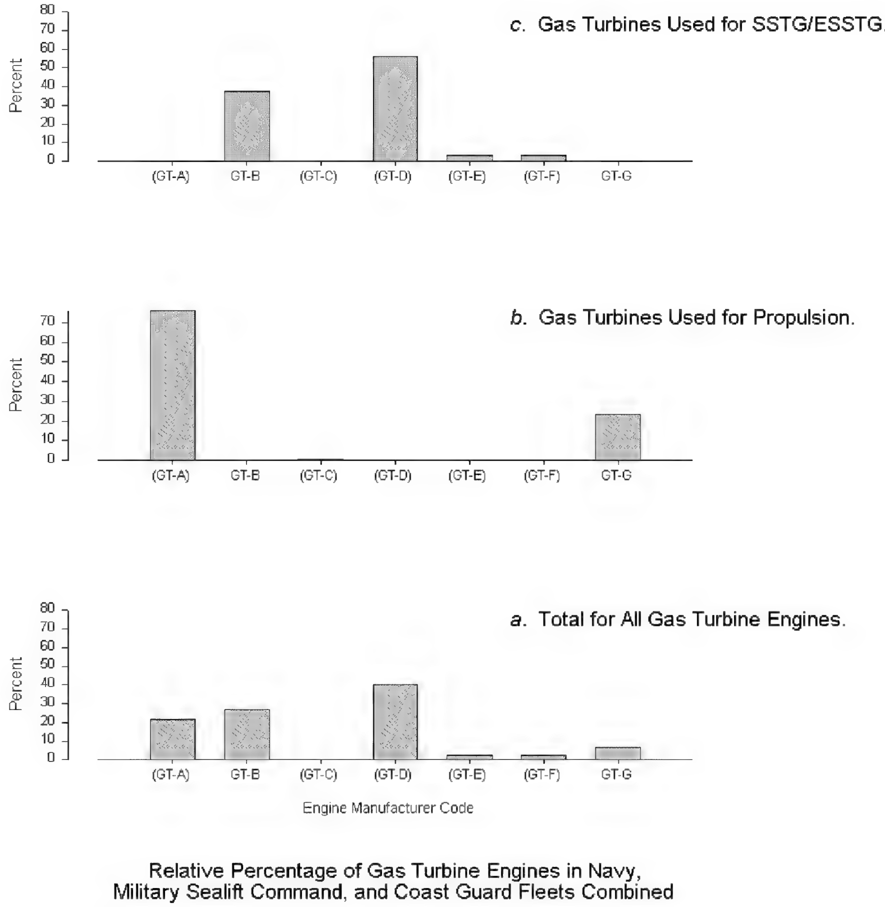
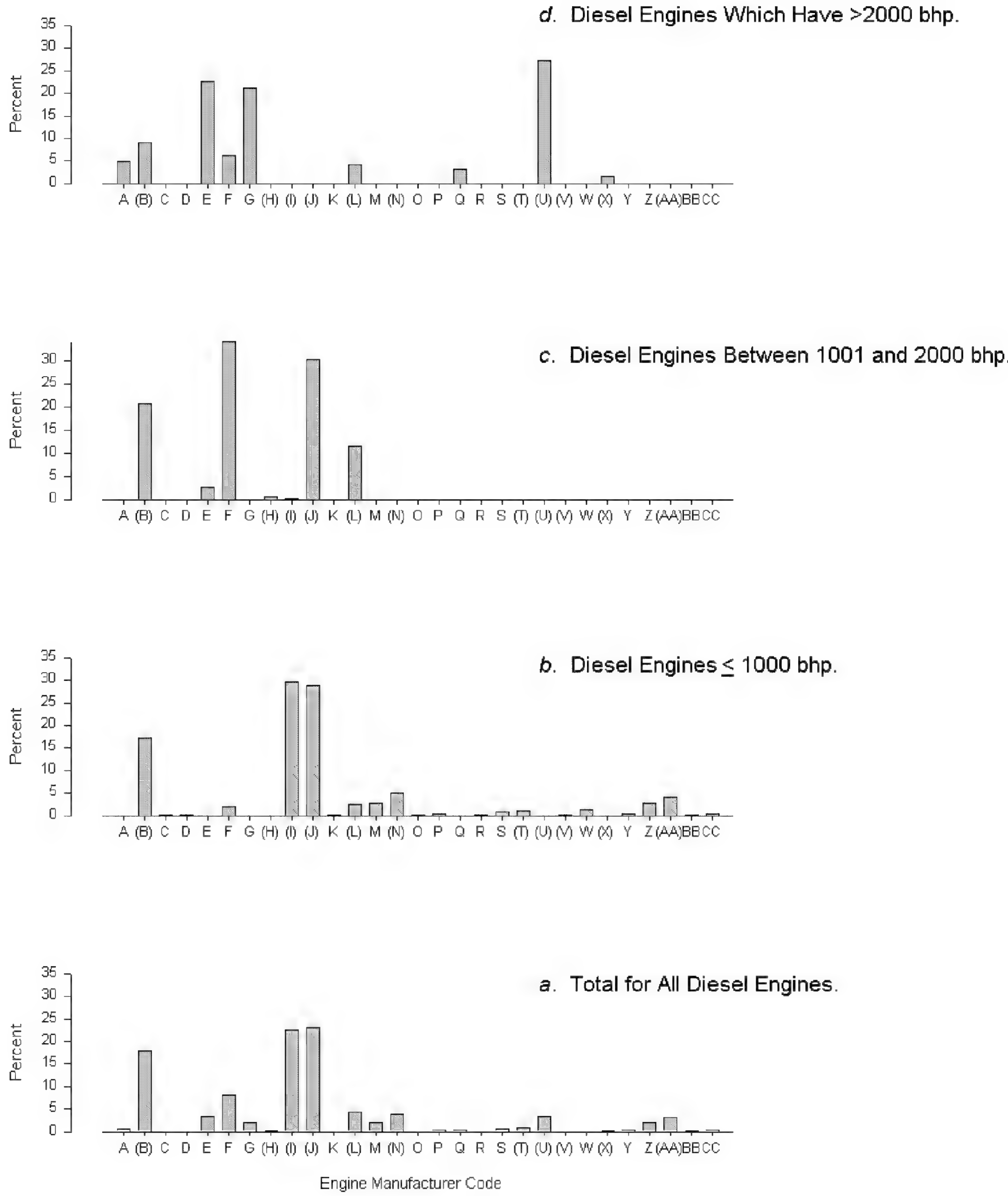


Figure 4. Relative Percentage of Gas Turbine Engines in Navy, Military Sealift Command, and Coast Guard Fleets Combined (NOTE: Manufacturer Codes Shown in Parentheses are Those From Which Responses were Received. Data Source: NSWCCD



Relative Percentage of Diesel Engines in Navy,
Military Sealift Command, and Coast Guard Fleets Combined

Figure 5. Relative Percentage of Diesel Engines in Navy, Military Sealift Command, and Coast Guard Fleets Combined (NOTE: Manufacturer Codes Shown in Parentheses are Those From Which Responses were Received. Data Source: NSWCCD

As stated earlier, the objective of this questionnaire was to obtain additional information to assess potential changes in future gas turbine and diesel engine technology. The following is a listing of the questions and summarized responses.

1. *What types of fuel can be burned in your engines without deleterious effects? We are especially interested in the type/grade of fuel your recommend for continuous use and emergency use. Please indicate below.*

	ISO 8217	**ASTM D 2069**	**ASTM D 975**	**ASTM D 2880**	**Others:**
Continuous					
Emergency					

Responses:

Specification	**Diesel**	**Gas Turbine**
ISO 8217	3 yes / 1 no	2 yes
D 2069	2 yes / 1 no	1 yes
D 975	7 yes	2 yes
D 2880	3 yes	2 yes
Others	EMA FQP1A (see Appendix F), JP-5, JP-8, F-76, D 1655	
Note: Several allow kerosene for emergency use only.		

2. *Do your engines have controls for specific emissions that were put in place in the last ten years? How and why were these controls achieved?*

    - Majority reported some type of controls or specific engine designs to meet emission requirements
    - Three companies report no specific controls/designs

3. *Does your company have developments in progress to enable off-specification fuels to be used? Please explain. If so, when do you expect these developments to be completed?*

    - Most have or are working on ways to use these fuels
    - Methods vary
    - Those in process expected in 1-3 years
    - One third report nothing current or planned

4. *Does your company qualify its engines to any particular type of fuel or fuel specification? Please elaborate.*

- Most common is commercial df-2 (df-1)
- Some include EPA or other government requirements
- One uses ISO 8217 distillate fuels
- Three use company specifications

5. *In your opinion, is the overall quality of commercial, distillate, marine fuels:*
   improving ___ remaining stable ____ decreasing ___?
   Please explain.

- Five reported decreasing
- Four reported remaining stable
- Four reported do not know/unable to answer
- One reported variable; some properties improving, some getting worse

6. *Are there fuel quality trends that will either positively or negatively affect your engines? Please explain. Are these trends located in particular areas of the world?*

- Lower cetane number
- Lower sulfur
- Fuels are getting heavier
- European fuels generally good
- Africa, Asia, Mid-east, South America reported as having poorer quality fuels by at least one company

7. *Are you aware of any future environmental regulations (between now and 2010) that will affect your engines or services? If so, please describe.*

- Future environmental regulations
- CARB, EPA, Tier 1/2/3, EEV, NO_x, CO
- EPA off-road emissions standards
- Euro3
- Numerous regulations that are all getting tighter

8. *Are there new engine designs in progress to meet future emission and fuel requirements? If so, please describe.*

- Fuel is not keeping up with new engine designs
- Fuel injection/timing changes
- Dry low emissions for gas turbine combustors

9. *What specific user-performed fuel testing and monitoring does your company recommend performing to assure satisfactory fuel quality and to maintain engine warranties?*

- In accordance with company service bulletins
- One reported a private label system for density, sulfur, cetane, distillation, temperature, cloud point, and microbes
- One reported ISO 8217
- Most companies recommend buying good quality fuel from a reputable supplier and good housekeeping to maintain quality
- Several recommend looking for water and microbial contamination

10. *Will engine modifications alone be able to meet new emission requirements or will fuel quality and composition also require changing? Please explain.*

- Majority reported that at least some engine changes needed; eight of those report fuel changes needed as well; specific improvements include:
  - Lower sulfur to 30-50 ppm
  - Higher cetane (>55)
- One reported working on a methane fueled engine

11. *Does your company recommend the use of fuel additives for engine performance improvement? If so, which additives and for which purpose.*

- None recommend routine use of additives
- About 1/3 report ok if added by the fuel supplier or to meet specific requirements
- One company uses DCI 4A for lubricity if SLBOCLE<3100
- Better to buy good fuel than to additive treat
- Two allow biocides in storage
- One recommends lube oil additives with low sulfur fuel

12. *Can shipboard fuel handling and filtration equipment aid in meeting future engine operating requirements? Please explain.*

- Majority report that the use of some type of fuel handling equipment will help
  - Examples include good filters, centrifuges, and water separators
- Three reported these equipment types are not necessary

13. *If fuel quality and/or composition require changing, what specific fuel changes will be necessary to give satisfactory operation in either current or future engine designs? As an example, should future fuels be cleaner because of smaller clearances in engine components such as fuel injection equipment?*

Most Recommended Changes Including:

- See EMA FQP1A (recommended guideline on premium diesel fuel)
- Lower sulfur
- Higher cetane number
- Cleaner -- finer filtration
- Lower aromatics
- Lubricity additives

14. *What is your company's policy on the use of alternative liquid fuels such as biodiesel, di-methyl ether, and fuels from Fischer-Tropsch processes. Please explain.*

- at this time, five companies consider them on a case-by-case basis
- Three allow them as a blend with diesel fuel
- One allows 100% biodiesel, DME (dimethyl ether), and Fischer-Tropsch
- One company allows use once the engine is out of warranty
- Three report none or emergency only
- None specifically disallowed or rejected the use of alternative fuels

15. *In your opinion, which alternative liquid fuels are suitable for marine use? Please explain.*

- Two reported fuels must meet company specifications
- Five have no data or recommendation
- Three diesel companies allow aviation distillate fuels
- Different for gas turbines -- more choices

16. *The following is a list of possible fuel-related problems. Has your company experienced any of these problems with your engines? If so, is it a significant problem and is the frequency of the problem increasing?*

Problem	Encountered? Y/N	Significant ? Y/N	Increasing Frequency? Y/N
Abrasion from high levels of ash			
Abrasion from high levels of catalyst fines			
Incompatibility/Instability			
Low temperature corrosion from sulfur			
High temperature corrosion from vanadium			
High viscosity			
Low viscosity			
Incomplete combustion			
Chemical reactivity of fuel with engine components			
Injection system problems			
Ignition delay			
Fuel contaminated with used lubricant, waste products, or other poor quality blend components			
Deposit formation on hot surfaces			
Poor lubricity			
Excessive water contamination			
High pour point or cloud point			
Filterability			
Other			

- Every problem was reported as having been encountered by at least one company
- Six companies reported encountering low temperature corrosion from sulfur and excessive water contamination
- Five companies reported incomplete combustion, high temperature deposits, and lubricity

Most of the respondents see environmental regulations getting tighter. Most of the respondents reported that fuel quality is remaining stable or getting worse. Many of the companies see the need to lower sulfur contents and raise cetane number. As expected, engine design changes are continuing. The use of alternative fuels is likely to increase.

C. Future Engine Technologies

This section is a summary of information gathered from various sources other than the engine technology questionnaire. It is divided into gas turbine engines and diesel engines but is in no other particular order. Not all of the information presented is specifically concerning marine applications.

1. Gas Turbine Engines

The U.S. Navy began using gas turbine engines for ship propulsion in the early 1970's. Gas turbines are also widely used for electric power generation. They provide more power for a given size/weight, longer life and higher reliability than comparable diesel engines. Gas turbine engines also have shorter engine start-up times than steam turbine engines in addition to lower maintenance and repair costs.

One disadvantage associated with the use of gas turbines is higher fuel consumption. For this reason, many modern marine propulsion systems use a combination of diesel and gas turbine engines. These are called CODOG (Combined Diesel or Gas Turbine) systems.[33] The diesel engine is used during low power and cruise operation and the turbine is used whenever high speeds are needed. The CODAG (Combined Diesel and Gas Turbine) arrangement is also used. The CODOG/CODAG systems are in limited use within the U.S. Coast Guard but are not used in U.S. Navy vessels.

In the future, gas turbine power plants, either through direct mechanical or electric drive, will be the most attractive choice for Navy surface combatants. There is work underway for next generation propulsion systems. However, lab testing, small-scale shipboard development and testing to final large-scale shipboard implementation will require at least 30-40 years before these systems are available.[34]

In the mean time, during the development of the next generation system, the Gas Turbine Energy Conservation Program was developed. The purpose of this program is as follows:

- Advancement and implementation of gas turbine technology through:
  - Improvement of U.S. Navy marine gas turbine efficiency and fuel consumption through the adaptation of industry and other DOD technology advancements.
  - Implementation of technology improvements quickly into the fleet in the most cost effective manner to provide the greatest return on investment.
- Maximize energy conservation by optimization of gas turbine operating profiles and overall propulsion and power generation plant management.
- Investigation of the applicability and cost effectiveness of next generation gas turbine engines operating in a U.S. Navy marine environment to implement energy conservation technology into future Navy platforms.

Improvements derived from this program will be made to allow the possible future application of alternate fuels and fuel quality changes. In addition, this program will utilize the philosophy successfully used in the Design, Development, and Implementation Program during the past 20 years, i.e., adopting technology advancements from outside the Navy in concert with utilizing the testing and implementation process used to adapt aviation engines to marine applications.

The Navy is not planning to adopt any major technical innovations in gas turbine technology such as the intercooled, regenerative (ICR) gas turbine. For the majority of the fleet, the Navy expects to be operating with General Electric model LM 2500 type technology for the next 10-12 years. New engine purchases over this time period will be those in current production. Only improvements with low technical risk and proven payback will be considered for surface combatants. The list of prerequisites (in decreasing order of importance) for incorporating new technology is:

- Workload reduction
- Operational availability improvement
- Energy conservation
- Emissions

It is expected there will be little change in current Navy gas turbine systems.

2. Diesel Engines

It seems apparent that while diesel engine manufacturers will continue to work to satisfy customer requirements, the more significant impetus behind future engine design changes will be environmental regulations. The information and references cited below reflect the trend and present examples of some of the technologies under investigation. The interested reader is encouraged to review the references for further information.

A combination of diesel engine technologies is emerging as the predominant means of meeting anticipated future emissions requirements. The suite of technologies includes direct injection, turbocharging, and common-rail injection. An engine employing these technologies is a

candidate propulsion technology in the Partnership for a New Generation of Vehicles.[35] Several references are available for additional information concerning these technologies[36, 37, 38,39]

Morgan, et al[40], reported the results of a study to develop a heavy-duty diesel engine capable of meeting European NO_x and particulate matter standards for the year 2005 and beyond. It is their contention that the objectives cannot be met using conventional turbocharging systems and a cooled exhaust gas recirculation (EGR) emissions control strategy. The work resulted in a concept that uses a single stage, wastegated turbocompound system. This system also utilized a short-route EGR configuration. Additionally, the authors reported that exhaust aftertreatment systems, such as particulate traps, might provide marginal benefit. Other aftertreatment systems, such as selective catalytic reduction (SCR), offer significant benefits but are not considered feasible for model year 2005.

Stebler, et al[41], reported NO_x reductions of 30 to 50% in a medium size, medium-speed direct injection diesel engine. The engine was equipped with a Miller System, a newly developed High Pressure Exhaust Gas Recirculation System, a common rail system, and a turbocharger with variable turbine geometry. Power output, fuel consumption, soot, and other emissions were held constant during the testing.

According to Bailey,[42] NO_x adsorbers offer a reliable alternative to catalysts for reducing diesel engine NO_x emissions. Catalysts continuously convert NO_x to N_2. Adsorbers are materials that store NO_x under lean conditions and release and catalytically reduce the stored NO_x under rich conditions. The typical sulfur levels in current diesel fuels present a significant challenge for the application of NO_x adsorbers. Bailey reports that with appropriate developmental work and control of fuel sulfur levels, adsorber systems could provide sufficient NO_x control to meet future diesel engine emission levels.

Khair[43] was able to meet future heavy-duty diesel engine emissions goals using a combination of exhaust gas recirculation (EGR) and passively regenerated traps. The reduction in NO_x and particulate matter came with a fuel consumption penalty of about 5%. Also, hydrocarbon and carbon monoxide emissions tended to increase, especially when the trap was loaded with particulate matter. The author believed these penalties could be curbed by optimizing the engine system.

Park and Park[44] used EGR in combination with water emulsified fuel to achieve future emission goals for both NO_x and particulate matter. This approach also caused some changes in carbon monoxide emissions depending on the load of the engine. Ishida, et al,[45] also found significant reductions (about 50%) in NO_x with no increase in fuel consumption or smoke with port water injection. They also found no discernable deterioration of lubricating oil properties.

Mayer, et al,[46] recently published the results of a four-year European investigation of methods to reduce diesel engine particulate emissions. It was their conclusion that particulate trap technology is the only acceptable choice among all available measures. They found several systems with filtration rates of more than 99% for ultra-fine particulates. Traps offer the advantage that they can be fitted to new engines or retrofitted to existing engines. Several methods will work for regenerating particulate traps. In addition, traps do not produce secondary emissions.

Fanick and Bykowski[47] successfully demonstrated that a plasma reaction bed, used as an exhaust aftertreatment, is capable of reducing both particulates and NO_x simultaneously. In the period since, the use of plasma discharges for the removal of NO_x, and other pollutants from engine exhaust has grown.[48]

3. World-Wide Fuels Harmonization[49]

In December 1998, the American Automobile Manufacturers Association (AAMA), the European Automobile Manufacturers Association (ACEA), the Engine Manufacturers Association (EMA), and the Japan Automobile Manufacturers Association (JAMA) collaborated to publish a letter with the subject of "World-Wide Fuels Harmonisation." This letter presented their efforts to establish worldwide fuels recommendations. The objective of the effort "is to develop common, world-wide recommendations for quality fuels, taking into consideration customer requirements and vehicle emission technologies." The proposal described contained the specification for three categories of diesel fuel as follows:

- Category 1: Markets with no or minimal requirements for emission controls: based primarily on fundamental vehicle/engine performance concerns.
- Category 2: Markets with stringent requirements for emission controls or other market demands. For example, markets requiring US Tier 0 or Tier 1, Euro 1 and 2, or equivalent emission levels.
- Category 3: Markets with advanced requirements for emission controls or other market demands. For example, markets requiring US California LEV, ULEV, and Euro 3 and 4, or equivalent emission levels.
- Category 4: Markets with further advanced requirements for emission control, to enable sophisticated NO_x and particulate matter after-treatment technologies. For example, markets requiring US California LEV-II, US EPA Tier 2, and Euro 4 in conjunction with increased fuel efficiency constraints or equivalent emission standards.

Appendix F contains the detailed requirements for each of these categories of diesel fuel. Note that the sulfur requirement for Category 2 is 0.03 wt% (300 ppm) and 0.003 wt% (30 ppm) for Category 3. Category 4 diesel fuel is required to be sulfur free. Categories 2, 3, and 4 also contain requirements for fuel cleanliness, oxidation stability, increasingly narrow boiling ranges, and fuel lubricity.

According to the letter:

> "To meet future customer, environmental and energy challenges, the automotive industry is exploring advanced propulsion technologies world-wide. Category 3 has been defined as those requirements needed by advanced technologies as they exist today. It is anticipated that additional categories of petroleum-derived fuels, including gasoline and diesel fuel, will be established in the future as engines and emission control technologies evolve in response to these challenges."

In essence, the engine manufacturers have stated that they must have significant changes in the current diesel fuel specifications if they are to meet expected emissions regulations and customer requirements over the next ten years.

VIII. DESC AND NAVY FUEL AVAILABILITY CONCERNS

The mission of DESC is to provide the DoD and other government agencies with comprehensive energy support in the most effective and economical manner possible. The hierarchy of fuels used onboard ship is:

- **F-76:** Primary fuel.
- **JP-5:** Acceptable substitute on a continuous basis; also, the cold weather fuel.
- **MGO-PD:** Purchased through DESC bunker contracts—accounts for only about 4% of diesel fuel use
- **Commercial fuels:** These are emergency substitute fuels, they must meet the 60°C minimum flash point. The fuels, in order of acceptability, are ASTM D 975 Grade 2D, ASTM D 396 Grade 2, and ASTM D 2880 Grade 2GT.
- **Commercial MGO:** This fuel is purchased on the open market as a local purchase. It is the last "emergency fuel" on the list. This fuel is not under a DESC bunker contract.

From the Navy point of view, this means supplying fuel (primarily F-76 for shipboard propulsion) wherever it is needed worldwide. To achieve this goal, DESC writes contracts with fuel suppliers around the world. DESC also stores fuel for use by the Navy, and DESC even arranges to ship fuel to places where F-76 is not available. The availability of F-76 can be low or non-existent, especially in less industrialized areas of the world. Reasons for this include:

- The F-76 specification is comprised of many requirements, making it more expensive for refiners to produce.
- F-76 is considered a specialty military fuel, and thus is a niche market.
- Commercial marine fuel specifications are written for applications that are less demanding, and the fuel produced to them more abundant than that produced in accordance with the F-76 specification.

In emergency situations, specification waivers can be granted but this is the exception rather than the rule.

In general, commercial fuel specifications are written for a larger market but more specific for the engines in which it is used (diesels, gas turbines and boilers) and thereby usually result in

greater fuel availability. Greater availability, in turn, results in lower costs and less need to store or transport fuel to remote locations.

As the quality of middle distillate fuel throughout the world increases, the likelihood that any given fuel will meet Navy requirements also increases. It also means that the Navy should be in a position to consider a commercial fuel specification in lieu of F-76 and feel confident that the fuel will meet their needs. The Navy is working with ASTM to develop and standardize a Standard Specification for Long Term Storage Application Middle Distillate Fuel Oils. It is anticipated that this new specification will eventually replace the MGO-PD. It is much closer to serving Navy needs than any other existing ASTM or ISO specification. The intent is not to use the new ASTM specification to replace F-76, but to purchase stable fuel commercially when F-76 or JP-5 are not available. The Navy is convinced that many commercially available fuels already meet this specification. It is their assertion that this will not be a fuel that is specially made but a fuel that is specially certified. The table of requirements for this proposed specification for a commercial fuel to meet Navy needs is presented in Appendix G. This fuel is a composite between F-76 requirements and the requirements of commercial specifications such as ASTM D 975, ASTM D 2069, and ISO 8217.

Historically, the F-76 specification has included a large number of properties to ensure that the Navy will have minimal fuel-related problems. Worldwide fuel surveys conducted by the Navy and DESC, have shown a trend toward a better quality "average" F-76/marine distillate fuel in the market. The Navy has taken the opportunity to modify selected properties' requirements in the specification through engine and fuel research projects based on the fuels obtained worldwide. This has had the effect of increasing the availability of fuel around the world. The logical conclusion to this trend is to drop the F-76 specification when a commercial specification fuel is found to meet the need, which is unlikely to occur because of NATO commitments. Of course, this action must be combined with a confidence that the quality of fuel available around the world is sufficient to meet Navy needs. These requirements would appear to be within reach because of the worldwide requirements for higher quality automotive diesel fuel, which carryover to supply the marine marketplace as well. However, the Navy must be certain that all critical fuel property requirements are being specified. It is not sufficient to rely on survey data that show increasing fuel quality for commercial fuels. There must be a specification to always ensure that the most important property requirements are met.

IX. CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations are grouped according to their relevance to engines, fuel, and emissions.

Engines

- Engine manufacturers around the world have joined together and published a Worldwide Fuels Charter to emphasize that there must be significant changes in current middle distillate fuel specifications if the manufacturers are to meet expected emissions regulations and customer requirements over the next ten years.

Fuel

- Since fuel sulfur levels will continue to drop worldwide, the Navy should be able to lower the sulfur specification in F-76 without adversely impacting the supply of fuel. However, there will be some areas of the world that lag behind this trend so the specification changes should probably be phased in.

- The mandated changes in fuel properties will result in an average worldwide diesel fuel that is more stable, cleaner, and cleaner burning.

- As fuel sulfur and aromatics decrease, fuel lubricity will probably become the issue of greatest importance. The sensitivity of fleet equipment to lower lubricity fuel is not known but is expected to be high due to the equipment's age.

- The Navy should investigate the potential for lubricity-related problems with their current engines and fuel systems. The investigation should include the consideration of additives to improve the lubricity of low-lubricity fuels. Of course, any additive used in Navy fuels must be shown to have no detrimental effects on the fuel, fuel system components, engines, and engine emissions and be added only at the refinery level.

- One of the reasons that many fuel manufacturers gave for not selling F-76 is the expense of certifying fuel to meet all of the F-76 requirements. The fact that F-76 is often considered a niche market only exacerbates the situation.

- The Navy and DESC should consider a move away from the MGO-PD to commercial fuel as worldwide fuel quality improves. The main concern with the use of commercial diesel fuels, in lieu of MGO-PD, is assuring satisfactory performance from a fuel purchased under commercial specifications, which usually have far fewer properties specified as compared to MGO-PD.

- One way to begin to address the concern over commercial fuel use is to work with standards-writing organizations, such as ASTM, to develop a commercial specification that more closely meets the requirements of F-76 than do current commercial fuel specifications.

  - Also, a new commercial fuel of this type would not be labeled as strictly an automotive diesel or marine diesel, it would be considered a multi-use fuel. This increases the potential market for the fuel (gas turbines, boilers, and diesel engines) and makes it a more favorable fuel to produce and sell.

  - This fuel could also be used for other applications that require improved stability characteristics. These applications include pre-positioned materiel, emergency/standby generators, and military vehicles with low fuel-turnover rates.

  - Properties that might be included in the new specification are flash point, water and sediment, viscosity, ash, sulfur, copper corrosion, cetane number, cloud point, carbon residue, color, density, demulsibility, particulate contamination, storage stability, and thermal stability.

- As a multi-use fuel, the fuel might be available in areas of the world that have traditionally sold little or no fuel that would meet the F-76 specification.

- A new commercial fuel could result in a better quality fuel that is more available, and less expensive than F-76. Reasons for this include:

1) The market for a commercially specified fuel would be greater than that for a specialized military fuel.
2) The commercial specification has fewer properties specified, as compared to F-76, which makes it simpler/less expensive for oil companies to meet.

- Conversion to a commercial fuel with increased storage stability would also potentially reduce the need to pre-position fuel since the market availability would be higher.

Emissions

- Worldwide engine emission/air quality standards are becoming increasingly restrictive. This is especially true for industrialized countries. However, even Asia and Africa are moving in this direction. This trend will continue.

- Tighter emissions regulations will result in some engine changes such as exhaust after-treatment, exhaust gas recirculation, and direct injection/common rail technology becoming more commonly used.

- Emissions regulations will impact the quality of middle distillate fuel as well. The largest changes in fuel quality will be mandatory reductions in the levels of sulfur, aromatics, and possibly nitrogen.

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Appendix A
Summary of "A Report on Regulations of Marine Vessel Emissions and Marine Fuel Composition"

Purpose

A recent study by Carnegie Mellon University finds that shipboard engines are among the world's highest polluting combustion sources per ton of fuel consumed. The study also suggests that a majority of pollutants attributable to persistent continental pollution actually come from vessels. The purpose of this study is to identify the legal regimes that address these issues.

Regulations Identified

There is no international regulation currently in force, such as a multinational convention, which addresses air pollution from ships. An international standard, not a regulation, ISO 8217:1996(E) restricts the fuel composition of ships to 5% sulfur content, but as a standard, it imposes no obligations upon any nation, even ISO member states.

MARPOL 73/78's Annex VI, which was opened for ratification as of 1 January 1998, focuses on two sources of air pollution from ships: sulfur oxides, to be regulated by fuel composition; and nitrogen oxides, to be regulated by stringent engine technical specifications. While Annex VI is a significant proposal if only because it is the first of its kind, it does little to actually change the international norm of fuel composition with relation to sulfur emissions. Nevertheless, it may be the foundation upon which future marine vessel emission regulations are promulgated.

There is one international-regional program that addresses air pollution from ships, the Helsinki Convention, whose membership is comprised of the Baltic Sea Area countries. The Convention allows its Commission, HELCOM, to make Recommendations regarding the level of sulfur in marine fuels for the coastal area as well as restrictions regarding emissions from ships. HELCOM has already addressed these issues in specific Recommendations, and as such, the member states have been expected to implement national regulations. However, none of the HELCOM Recommendations have actually been implemented. This Convention acts primarily - and purposefully - as a catalyst for much of the impetus behind IMO’s formulation of Annex VI.

On the national level, only one country has a specific policy already in place that directly addresses air pollution from foreign flagships. Sweden’s Tripartite Agreement is not a Swedish law but a voluntary policy adopted by the Ports and Stevedores Association (SPSA) in conjunction with the Swedish National Maritime Administration (SMA) and the Swedish Ship Owner’s Association. The agreement punishes ships that pollute and rewards ships that emit low levels of air pollutants through a tax/tariff program. The Swedish government has not adopted a formal law, but has given the voluntary program its official authorization.

Both the European Union (EU) and the United States have appropriate legislation "in the works" to follow Annex VI. The rest of the countries and regions examined have various levels -- federal, state, and local/port -- of environmental legislation for air

pollution, some very stringent, like Canada and Japan, and some almost non-existent such as in various African and South American countries. In almost all cases, marine engine emission and fuel composition is not specifically addressed.

Conclusion

Annex VI of MARPOL 73/78 is the only international regulation addressing this issue and only spotty regional and nation-specific compacts and legislation are in place globally. Concomitant with growing recognition of the problems of vessel air pollution is a growing trend to mandate significant reductions in sulfur oxide and nitrous oxide emissions as well as other contaminants. The study found that there is an overall developing sense of environmental stewardship by companies in response to factors such as customer demand and legislative initiatives.

This information is important in its own right, even though much of it pertains primarily to heavy marine fuels. Additionally, it is important as an indicator that regulatory agencies are now beginning to look at marine sources of air and water pollution. It is reasonable to assume that as regulators attempt to reduce pollution from all sources; and, as the percentage of the worlds shipping that operates on middle distillate fuels increases, the number and severity of controls on middle distillate marine fuels will increase.

APPENDIX B
Refinery/Oil Company Questionnaire

DISTILLATE FUELS QUESTIONNAIRE

Interviewee Background Information
(This section is to be completed prior to arrival at interview)

1.) Date of Interview:
(Day) (Month) (Year)

2.) Name of Corporate Office:

3.) Mailing Address of Corporate Office:

4.) Interviewee Name:

5.) Position Title/Job Function:

6.) Telephone: ________________________ Facsimile:

7.) E-Mail Address:

Note: Additional personnel present during interviews: Please have any other personnel participating complete the separate page included at the end of the survey.

Part I - Crudes/Feedstocks

1.) Please fill in the table below for the types and sources of current crudes or feedstocks the facility receives to refine products.

Name of Crude/Feedstock	Crude/Feedstock Type (Please indicate Napthinic, Aromatic, or Parafinic; Sweet, or Sour: Heavy, or Light)	Volume (bbls) & Percent of Total Feed	Geographic/Company Source

2.) Do you expect your crude/feedstock slate to change over the next 10 years? If so, how and why?

3.) Do you expect any of the above crude/feedstock changes to affect your middle/marine distillate fuel production properties? If so, how?

Part II - Refinery Products

1.) Please fill in the table below with the various middle/marine distillate fuel oils currently being produced at your refinery/facility (i.e. heating oil, automotive diesel, marine gas oil, jet fuel, etc.). Please indicate the relative portion of these products (by percent or volume) to your total production. Identify them by product name/grade and the national, international or company specifications to which they are produced.

Product Name/Grade	Specification	Volume Produced (bbl/year)	Percent of Total Production

2.) For the fuels listed above please provide a copy of the specifications indicated if they are other than ISO or ASTM standard specifications. Automotive / marine distillate fuel specifications would be of particular value. We are not seeking company proprietary information, but rather the criteria that the fuels must pass to be sold under the stated specification.

3.) Please fill in the table below with typical inspection data for the fuels listed above.

1. List inspection data property names in left-most column. 2. List product names/grades across top row. 3. Indicate typical data values in cells

(Example Table)

Property Name	*Product Name/Grade*				
	Marine gas oil	*#2 Diesel*			
Density	*860 Kg/M³*	*850 Kg/M³*			
Viscosity @ 40°C	*4.0 mm^2/sec*	*3.5 mm^2/sec*			

Property Name	Product Name/Grade				

3.) (Continued) If you need more room for more <u>typical inspection data</u> please use the table below.

Property Name	Product Name/Grade				

4.) Do you expect your product slate to change over the next 10 years? If so, how may it change and why?

5.) Do you expect any properties of the middle/marine distillate fuel oils listed above to change in any significant way over the next 10 years. If so, how may they change and why?

6.) Do you expect the unit price of any of the middle/marine distillate fuel oils listed above to change over the next 10 years. If so, how and why?

7.) Do you presently, or would you be willing to produce middle/marine distillate fuel oil to meet either the U.S. Military Specification, Fuel, Naval Distillate, MIL-F-16884J (NATO F-76), or the U.S. Navy Marine Gas Oil Purchase Description (MGO PD)?
(The fuel property requirements are summarized in the table below.)

Summary of Fuel Property Requirements for MIL-F-16884J and MGO PD

Fuel Property	MIL-F-16884J	MGO PD
Acid Number mg KOH/100 ml	0.30 (max)	-
Aniline Point °C	60 (min)	-
Appearance [1]	Clear & Bright	Clear & Bright
Ash wt.%	0.005 (max)	0.01 (max)
Carbon Residue on 10% Btms,	0.20 (max)	0.35 (max)
Cloud Point °C	-1 (max)	-1.1 (max)
Color	3 (max)	3 (max)
Copper Corrosion	1 (max)	3 (max)
Distillation , 90% Point °C End Point °C Residue & Loss vol %	357 (max) 385 (max) 3.0 (max)	357 (max) - -
Demulsification minutes	10 (max)	-
Density @ 15.6°C Kg/M^3	876 (max)	876 (max)
Flash Point °C	60 (min)	60 (min)
Hydrogen Content wt %	12.5 (min)	-
Ignition Quality, Cetane Number Cetane Index	42 (min) 43 (min)	42 (min) 43 (min)
Particulate Contamination mg/L	10 (max)	-
Pour Point °C	-6 (max)	-
Sulfur Content wt %	1.0 (max)	1.0 (max)
Storage Stability mg/100 ml	1.5 (max)	-
Trace Metals, Vanadium ppm Sodium + Potassium ppm Calcium ppm Lead ppm	0.5 (max) 1.0 (max) 1.0 (max) 0.5 (max)	- - - -
Viscosity @ 40°C mm^2/sec	1.7 - 4.3	1.7 - 4.5
Water and Sediment vol %	0.05 (max)	0.05 (max)

[1] Fuels are considered to pass the appearance requirement with a rating other than “Clear and Bright” if they meet both the Water and Sediment requirement and the particulate Contamination requirement.

Part III - Processing Treatments

1.) Please fill in the table below with the various refining processes (i.e. atmospheric distillation, catalytic cracking, hydrotreating, etc) currently used at your facility to make the products listed in Part II above indicating the approximate percentage of each product's total volume derived from each treatment.

1. List all processes used in left-most column. 2. List all product names/grades across top row. 3. Indicate percentage of each product made by each process

(Example Table)

	Product Name/Grade				
Processing Treatments	*Marine Gas Oil*	*#2 Diesel*			
Atmospheric distillation	*65%*	*85%*			
Hydrocracking	*35%*	*15%*			

Processing Treatments	Product Name/Grade				

2.) Do you expect the current mix of processes used in both your refinery and in the refining industry overall to change over the next 10 years? If so how may it change and why?

3.) Are you aware of any emerging refining processes that could affect the properties of middle/marine distillate fuels produced by you or the refining industry overall? If yes, please describe. Also, please indicate whether your company is likely to implement such processes.

Part IV - Fuel Additives

1.) If your refinery/facility uses additives to improve the middle/marine distillate fuels produced, please indicate in the table below the additive trade names and chemical composition if known and check off the product name/grade in which they are used.

1. List product names/grades 2. Fill in additive trade names and chemical compositions in appropriate cell for the additive type.
3. Check off the appropriate box for the product containing the additive.
(Example Table)

Additive Classes	*AdditiveTrade Name*	*Additive Chemical Composition*	*Product Names/Grade*		
			M G O	*#2 Diesel*	
Cetane Improver		*Amyl-nitrate*		✓	
Storage Stability Improver	*Dupont, FOA-3*		✓		

Additive Classes	Additive Trade Name	Additive Chemical Composition	Product Names/Grades		
Cetane Improver					
Cold Flow Improver					
Detergent / Dispersant					
Lubricity Improver					
Storage Stability Improver					
Thermal Stability Improver					
Others (Specify)					

1.) (Continued) If you need more room for more additives or product names/grades please use the table below.

Additive Classes	Additive Trade Name	Additive Chemical Composition	Product Names/Grades		
Cetane Improver					
Cold Flow Improver					
Detergent / Dispersant					
Lubricity Improver					
Storage Stability Improver					
Thermal Stability Improver					
Others (Specify)					

2.) Do you expect the use of additives both in your products and in the refining industry overall to change over the next ten years? If so, how may it change and why?

Part V - Environmental Regulation Impact

1.) What current or future environmental regulations (international, national, regional, etc.), applicable to refinery operation/technology affect or may affect your production of middle/marine distillate fuels?

2.) What current or future environmental regulations (international, national, regional, etc.) are applicable to the middle/marine distillate fuels you produce?

3.) Are current environmental regulations responsible for any significant changes in the properties of the middle/marine distillate fuels? If yes, please explain.

4.) Are there any governmental air quality standards, either current or future, that may affect your company's ability to produce, or your customer's ability to use middle/marine distillate fuels? If yes, please describe.

5.) What directions or trends do you foresee for the next 10 years in environmental regulations regarding refinery operations, middle/marine distillate fuel composition, and engine emissions?

6.) Is the demand for better quality middle/marine distillate fuel increasing? What do you see as the trend for the next ten years?

7.) In the last ten years, have you been required to lower the total sulfur content of your middle/marine distillate fuels by either regulatory agencies or customer requirements? If yes, please describe those requirements.

8.) Regulators throughout the world are advocating total sulfur limits of 50 ppm for middle distillate and diesel fuels by the year 2005. Is your company, or would your company be willing to undergo changes in your refining processes to meet this reduced sulfur level? What would be the financial impact of such changes? Would reduced sulfur limits have any impact on fuel production?

Additional Personnel Present During Interviews

1.) Participant Name:

2.) Position Title/Job Function:

3.) Telephone: ________________________ Facsimile:

4.) E-Mail Address:

1.) Participant Name:

2.) Position Title/Job Function:

3.) Telephone: ________________________ Facsimile:

4.) E-Mail Address:

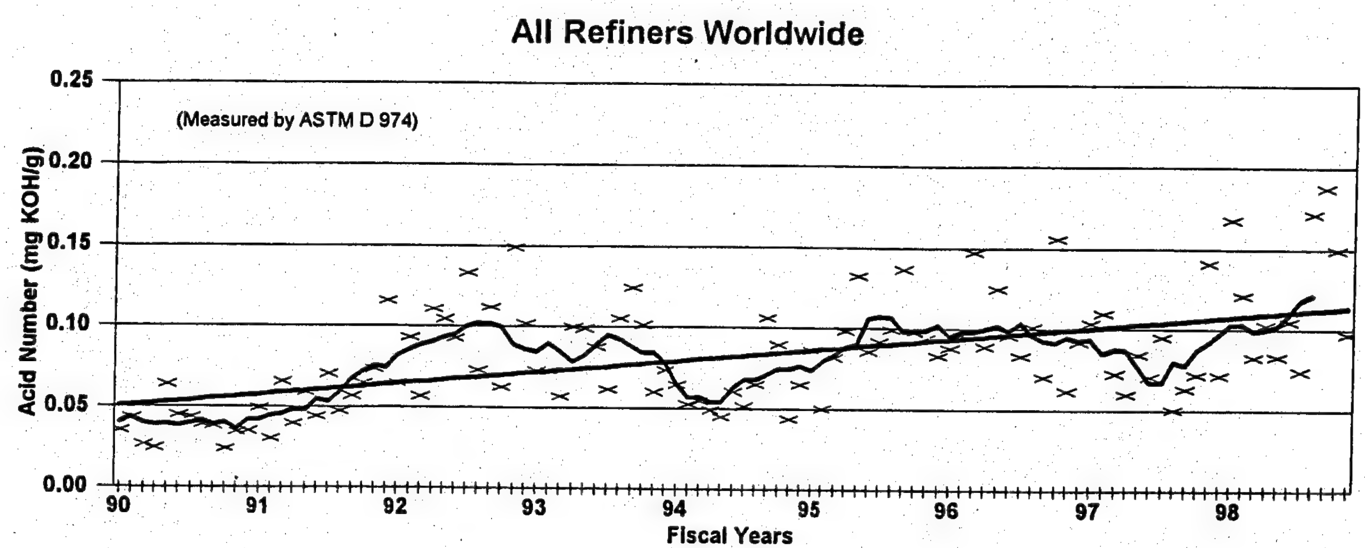
1.) Participant Name:

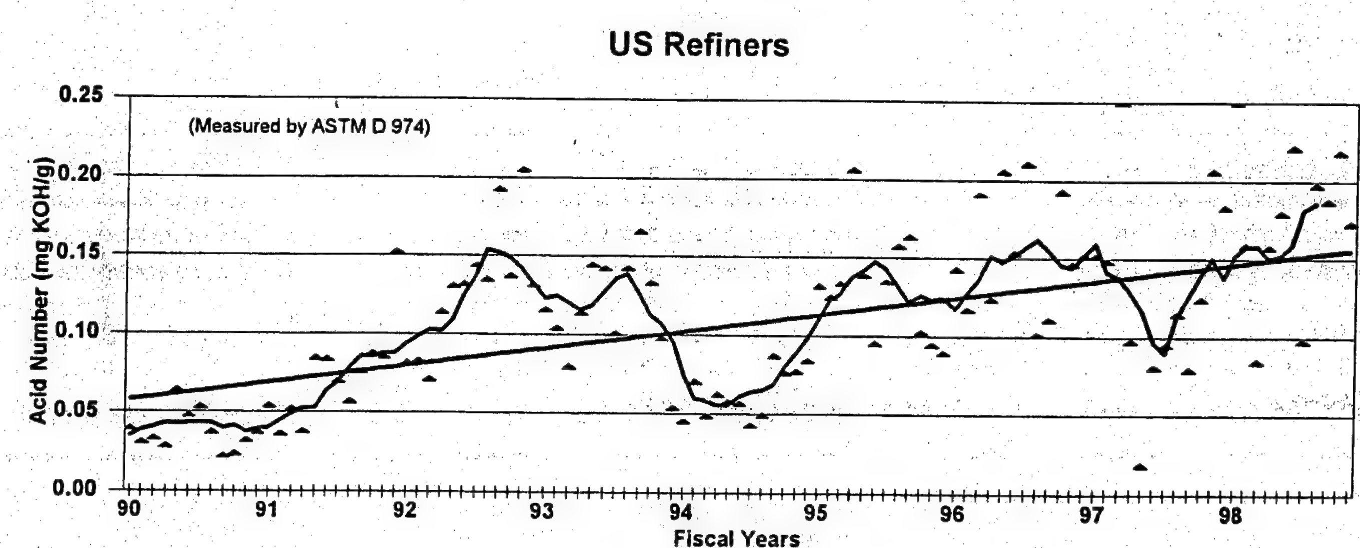
2.) Position Title/Job Function:

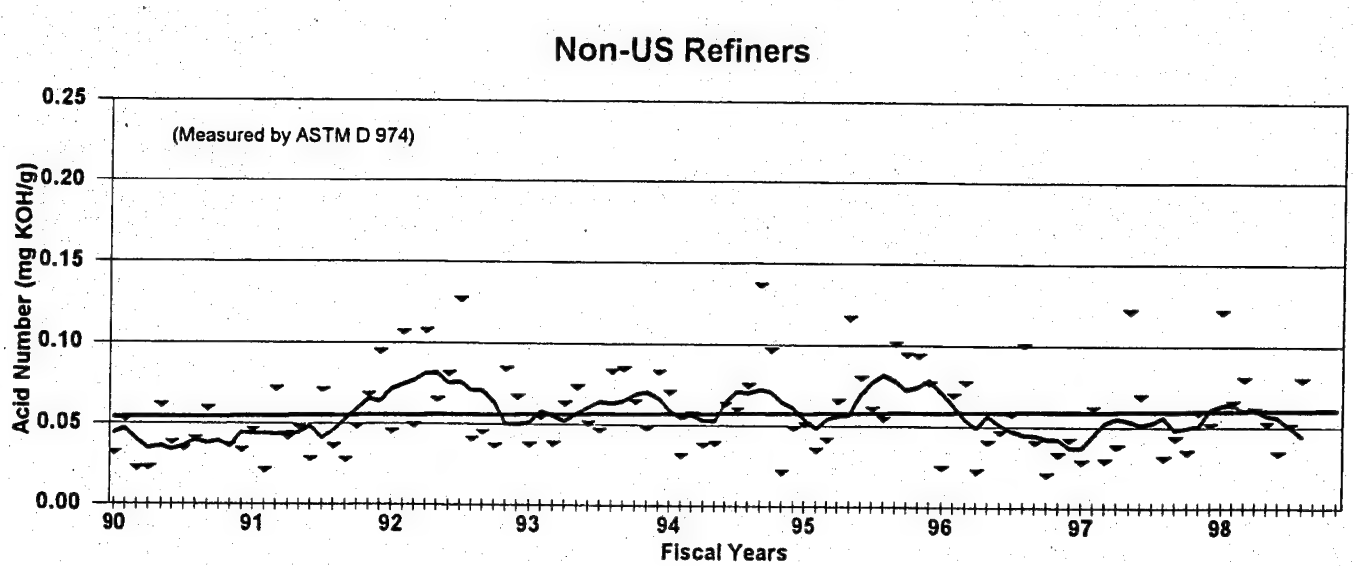
3.) Telephone: ________________________ Facsimile:

4.) E-Mail Address:

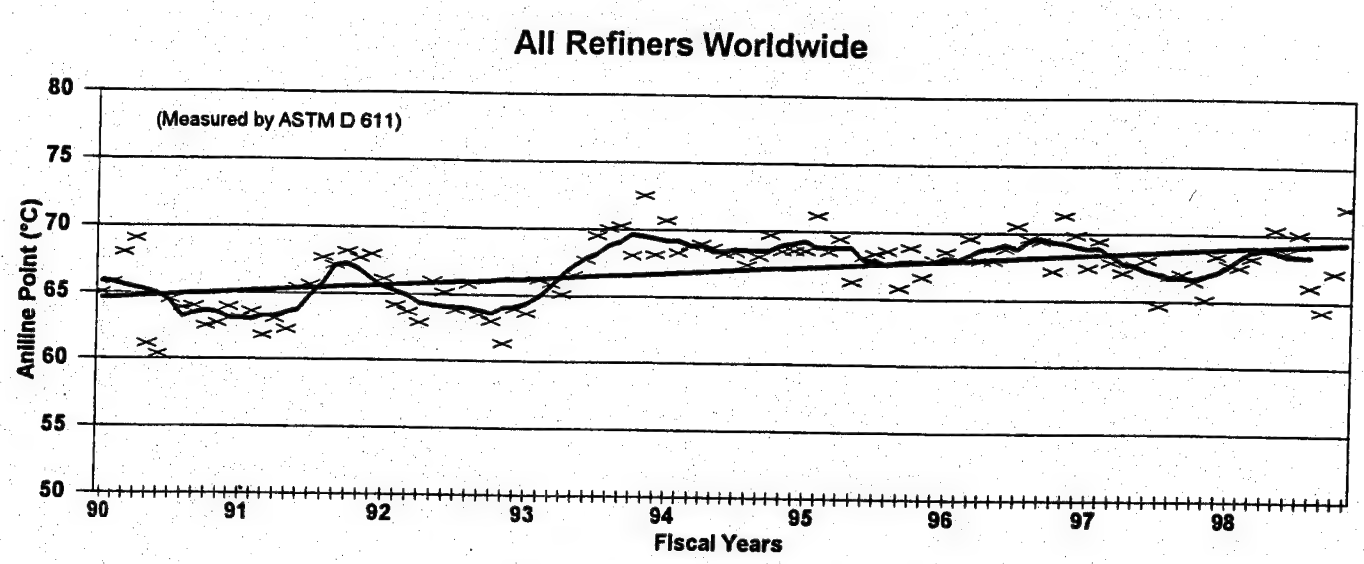
APPENDIX C
U.S. Navy Fuels Database Fuel Charts

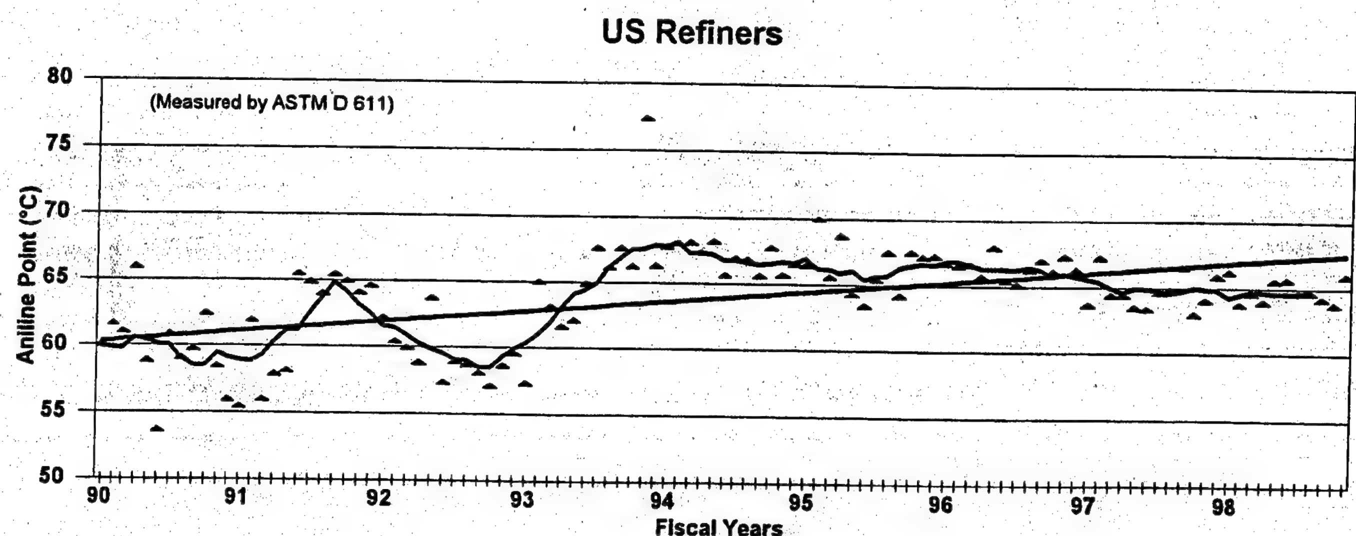


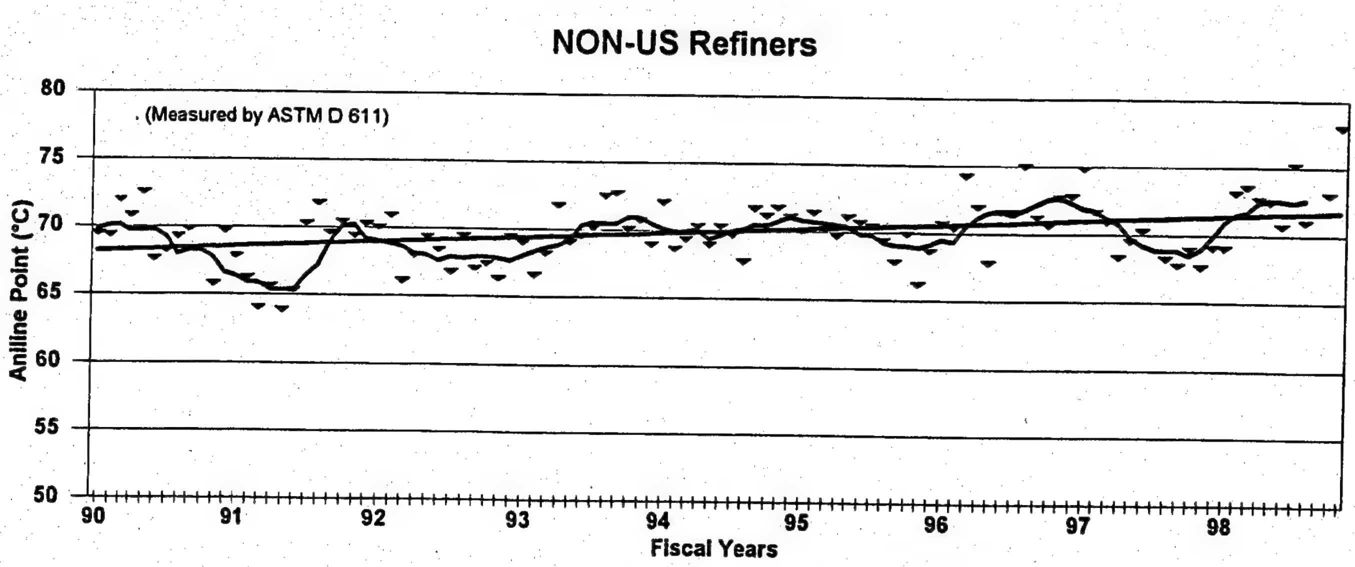




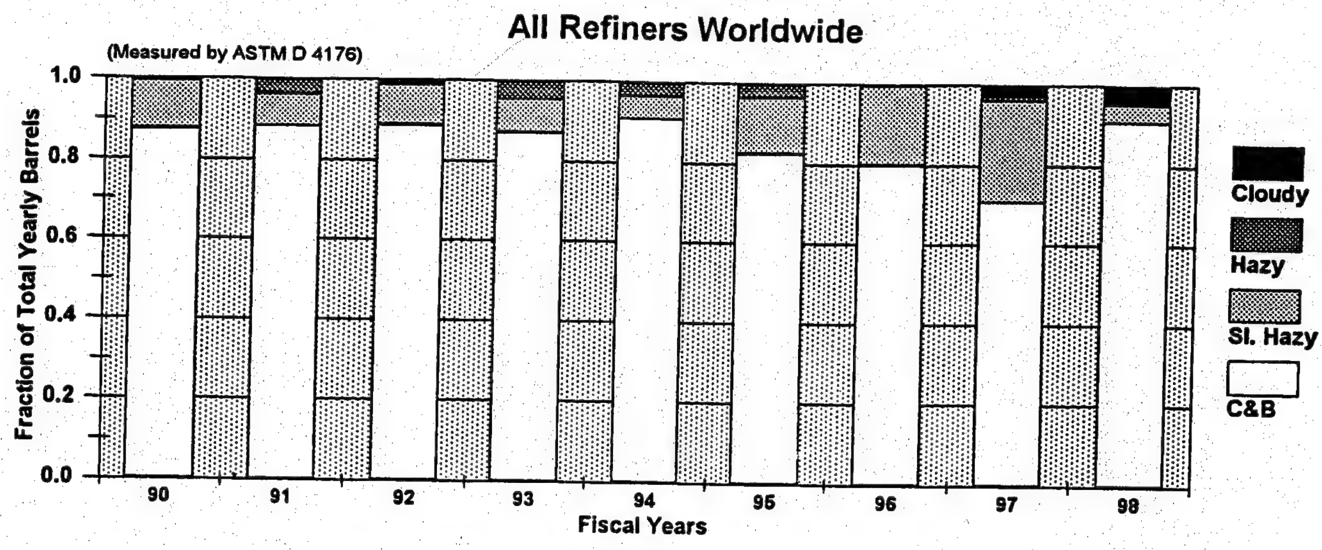
Acid Number of F-76, FY 90-98

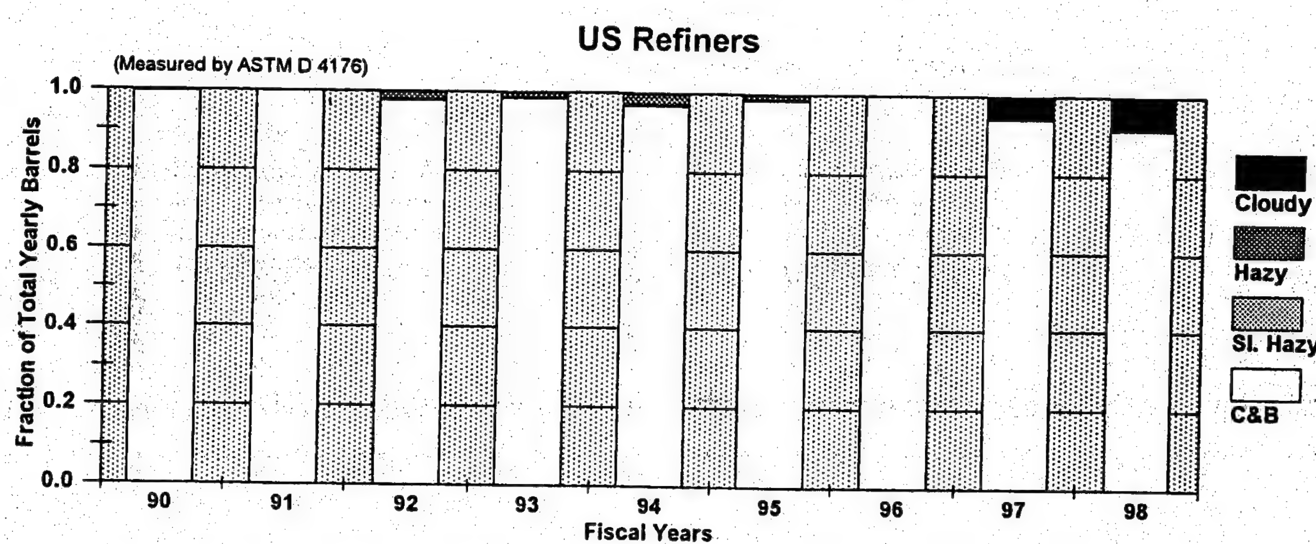


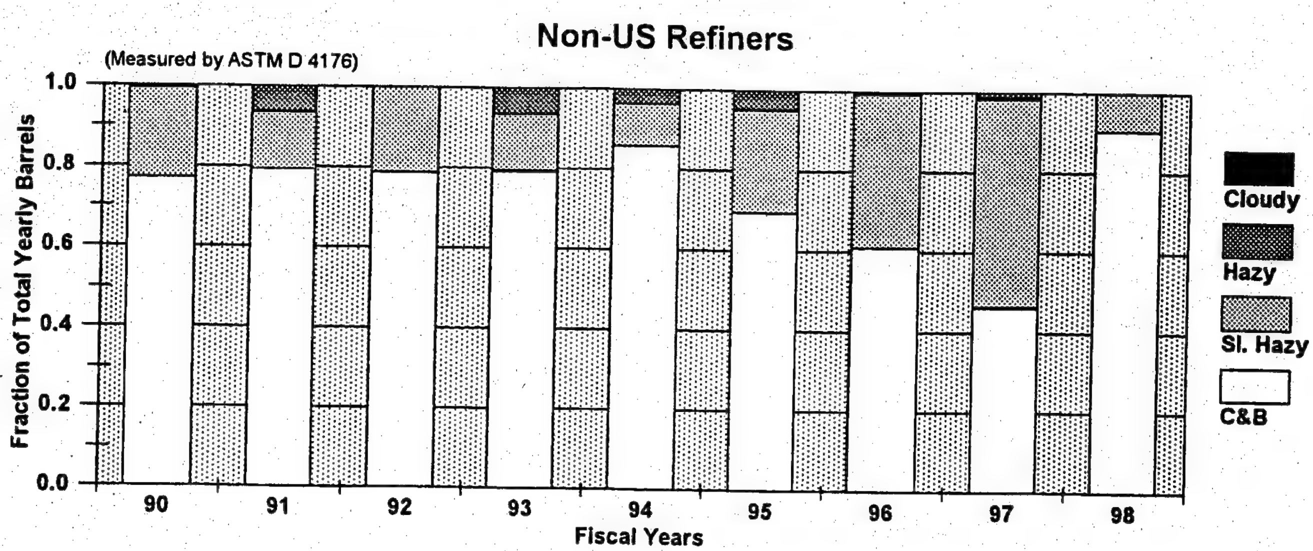




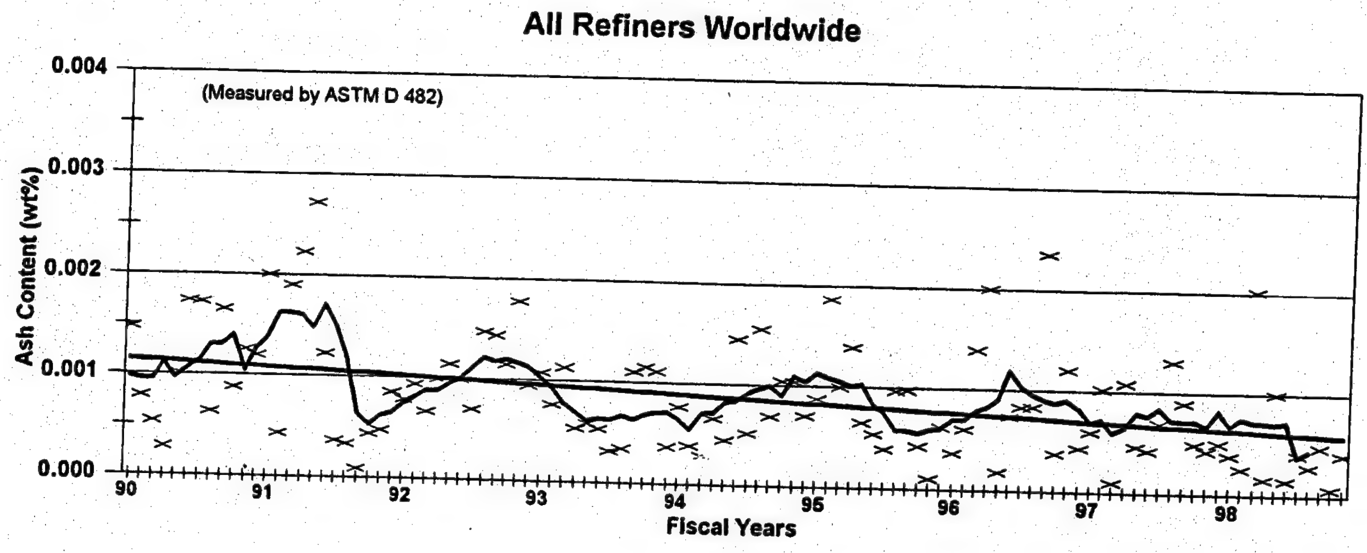
Aniline Point of F-76, FY 90-98

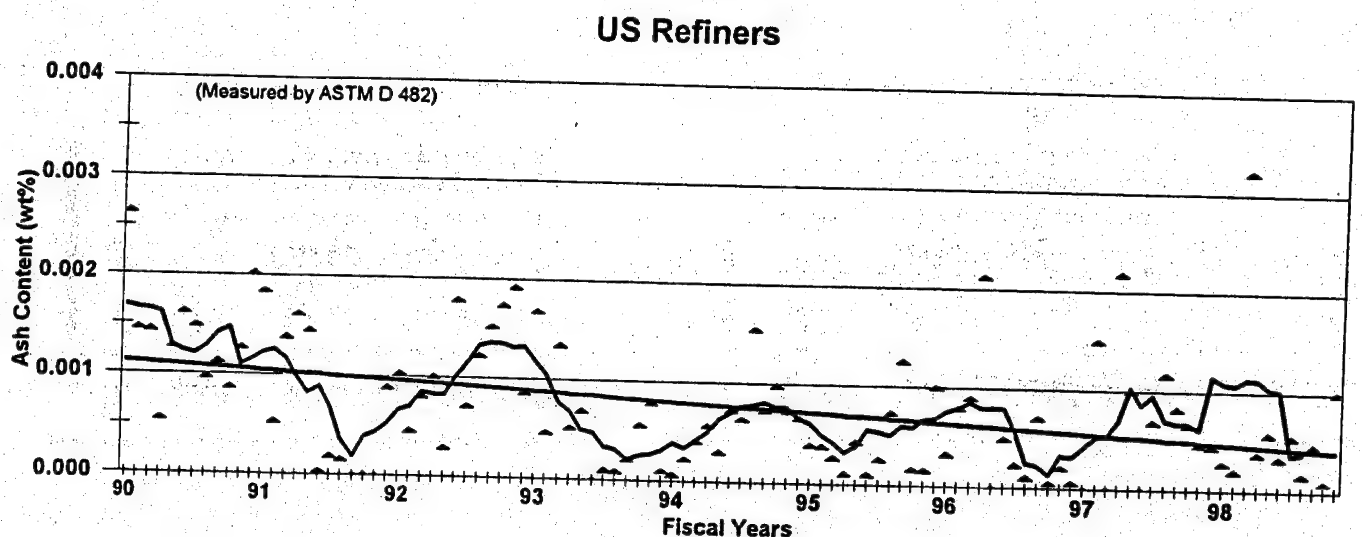


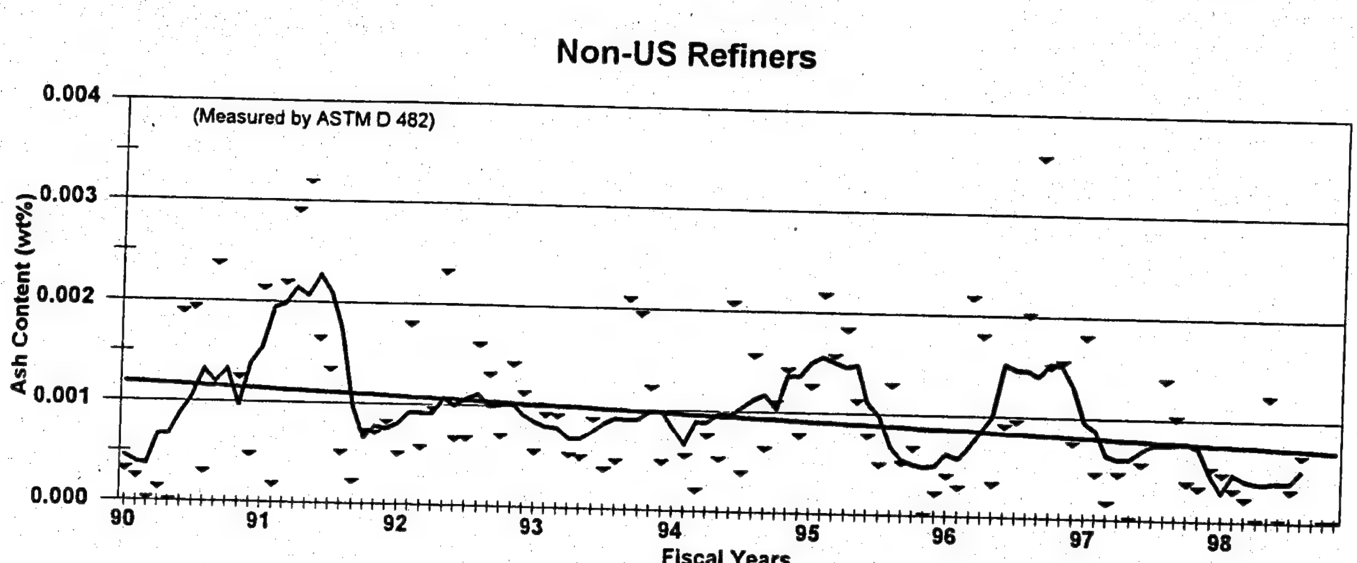




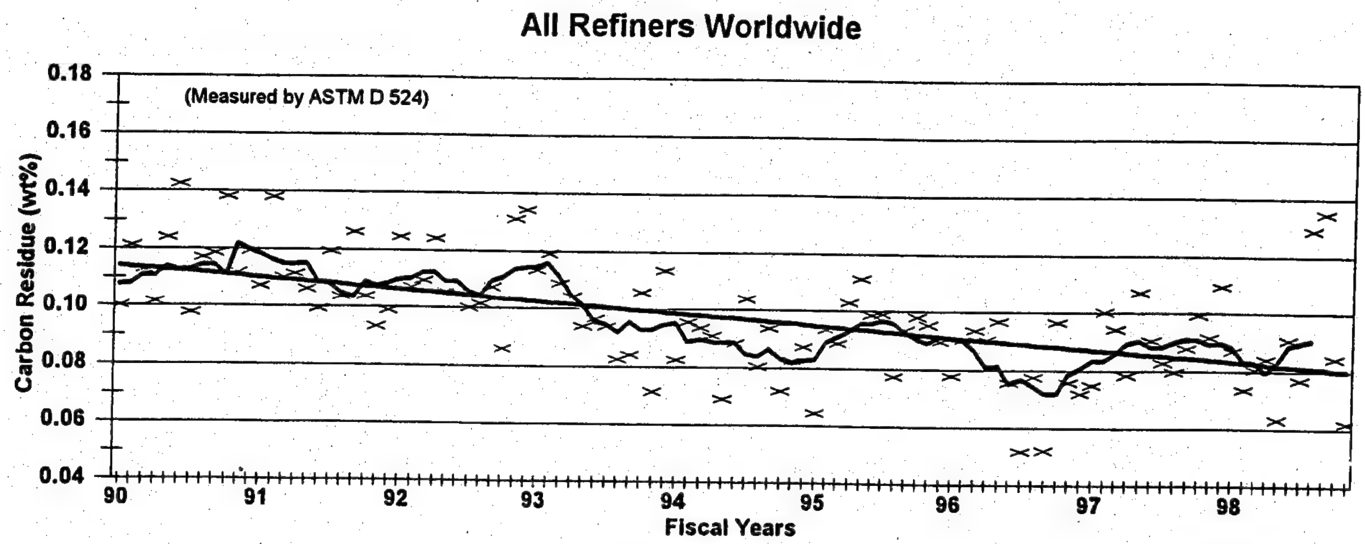
Appearance of F-76, FY 90-98

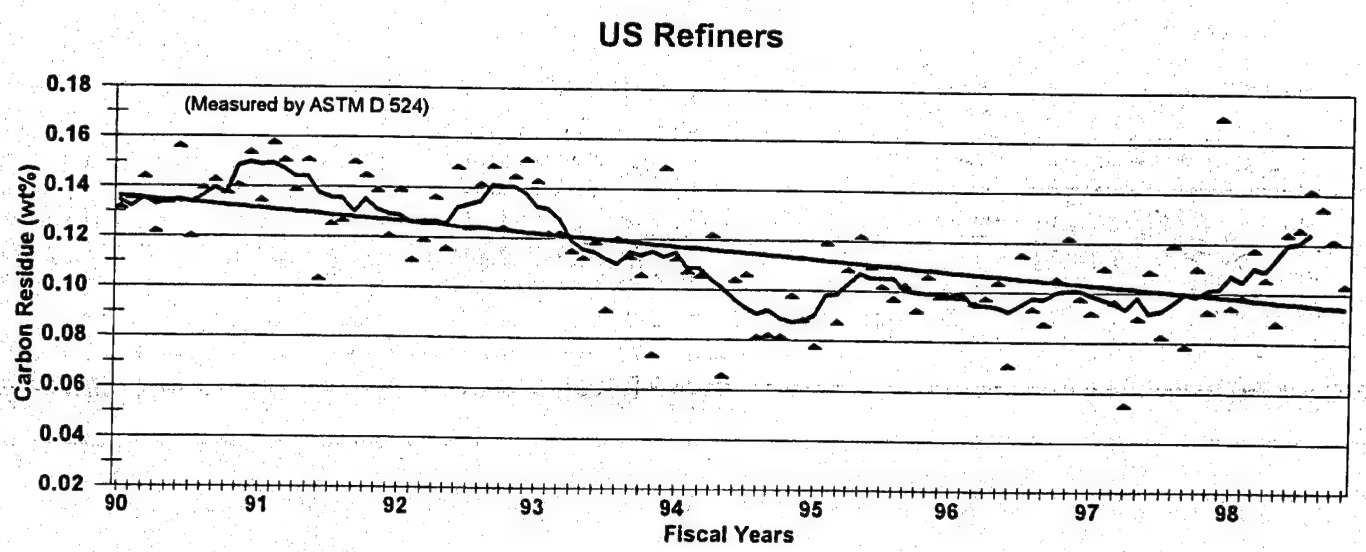


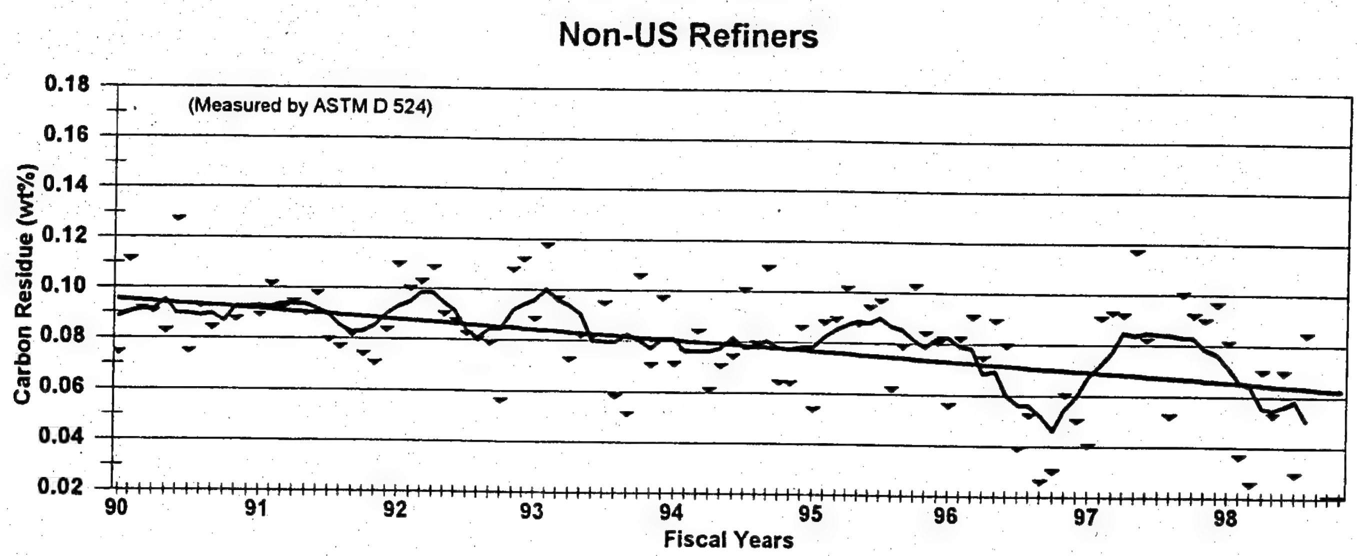




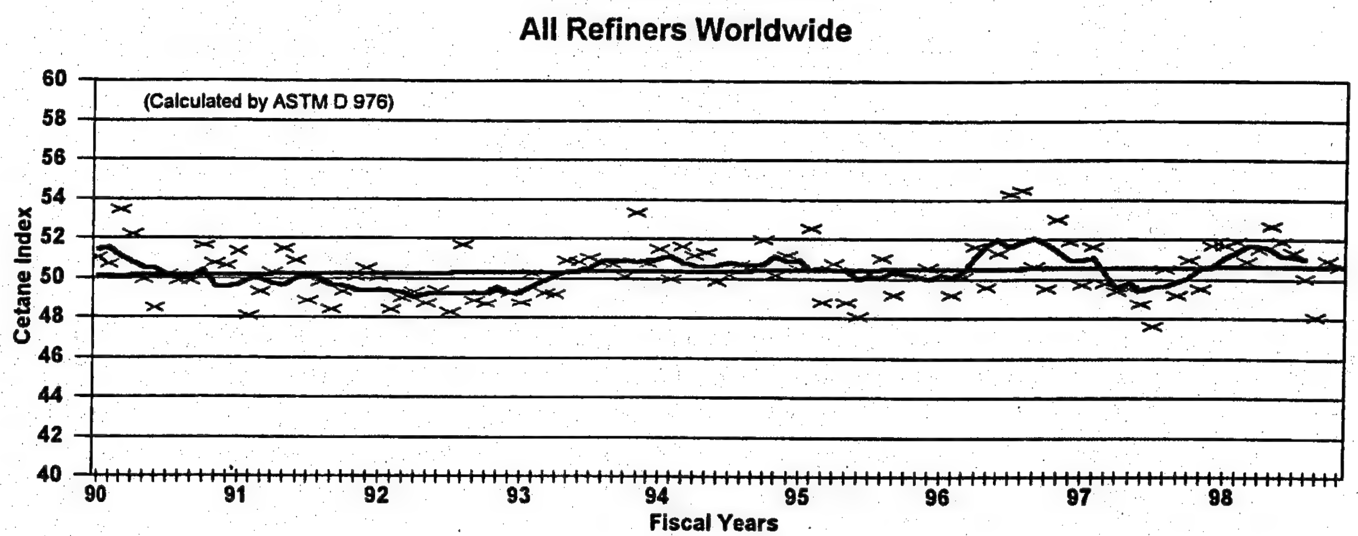
Ash Content of F-76, FY 90-98

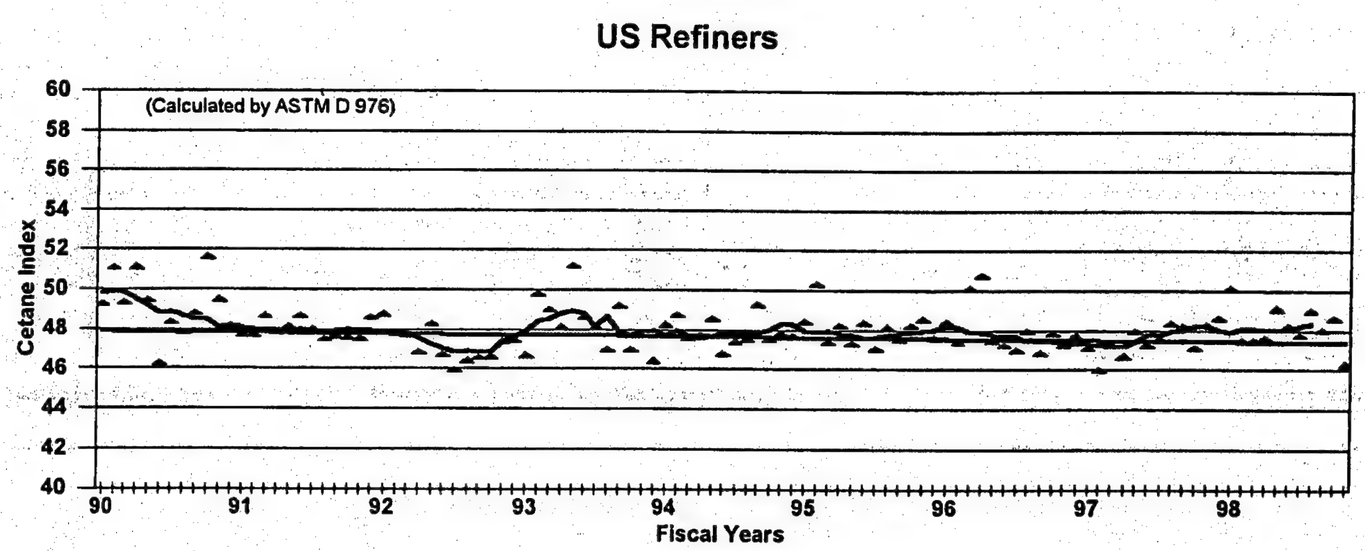


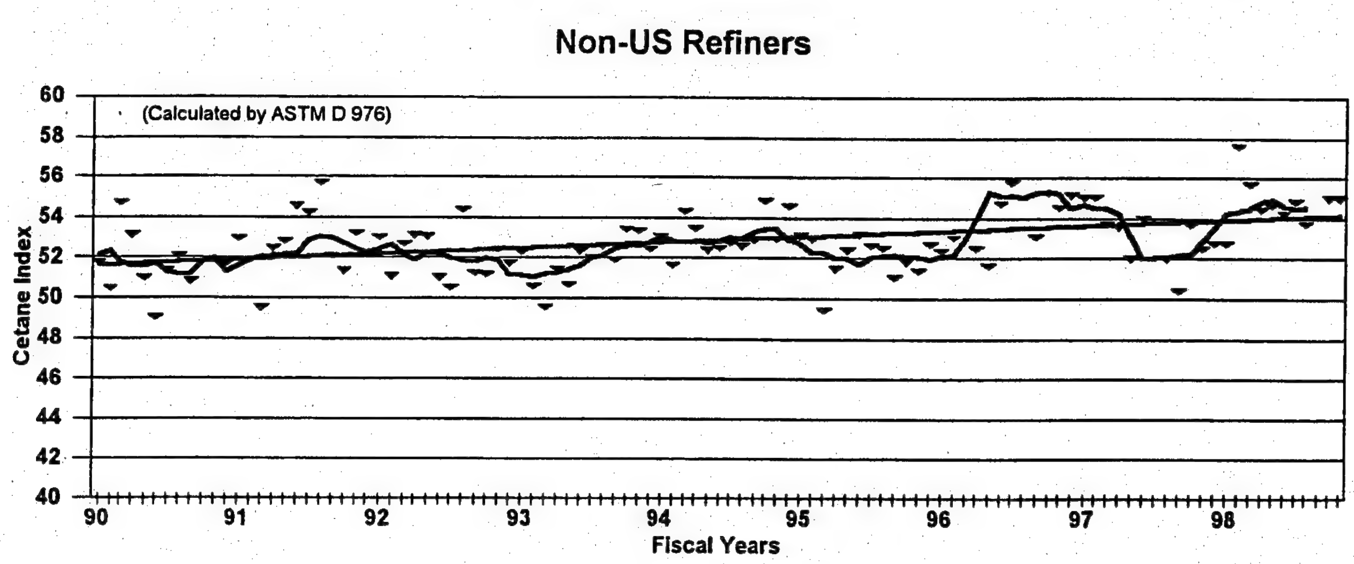




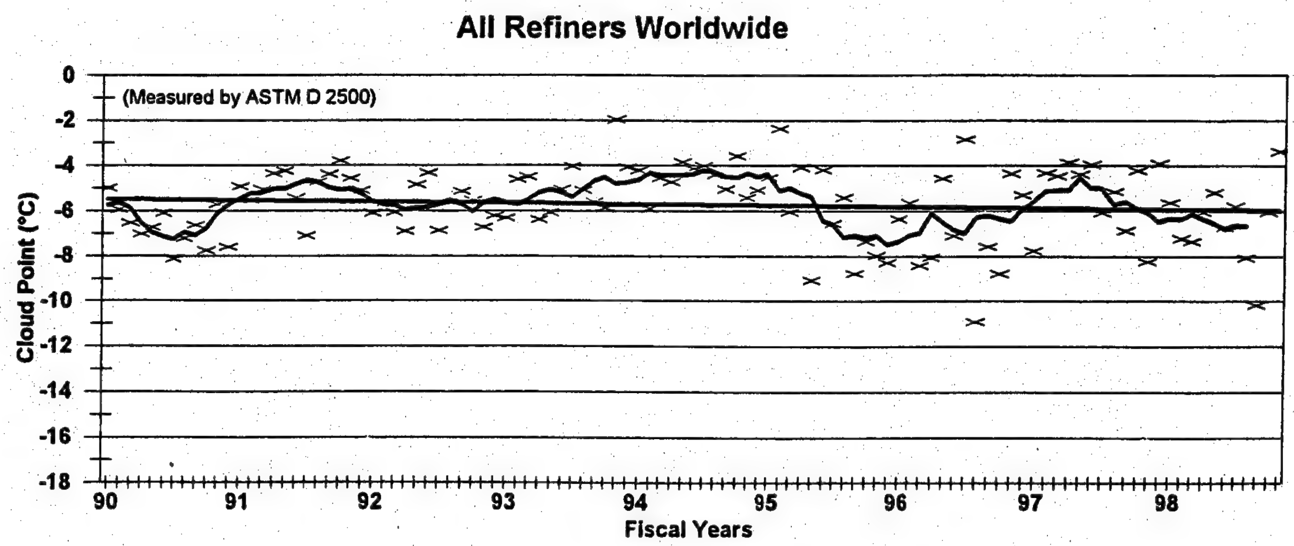
Carbon Residue on 10% Bottoms of F-76, FY 90-98

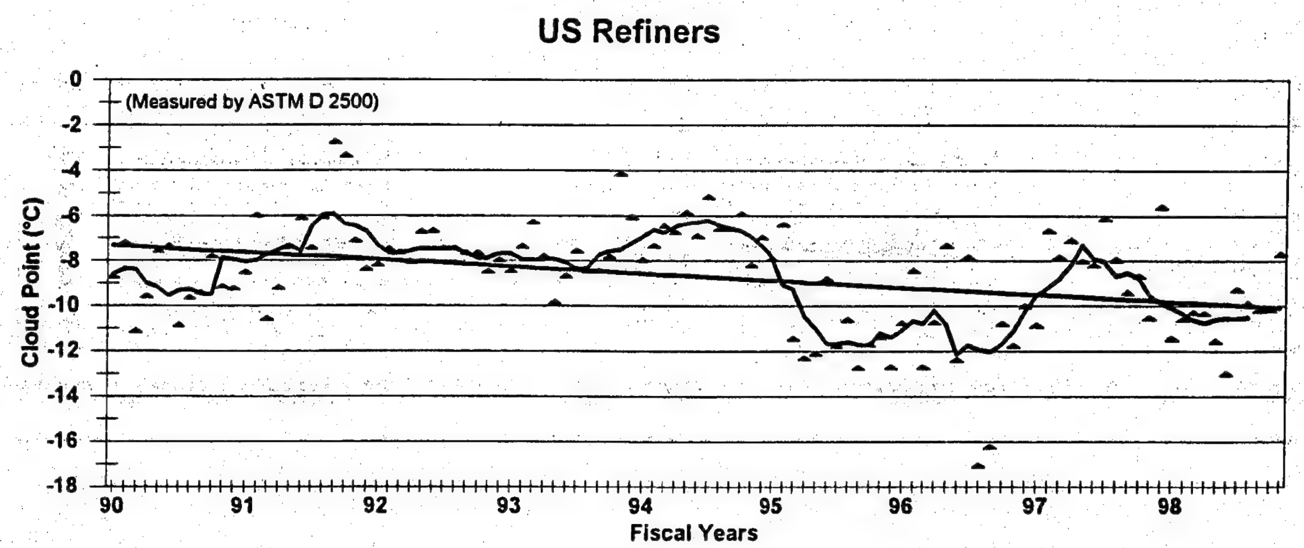


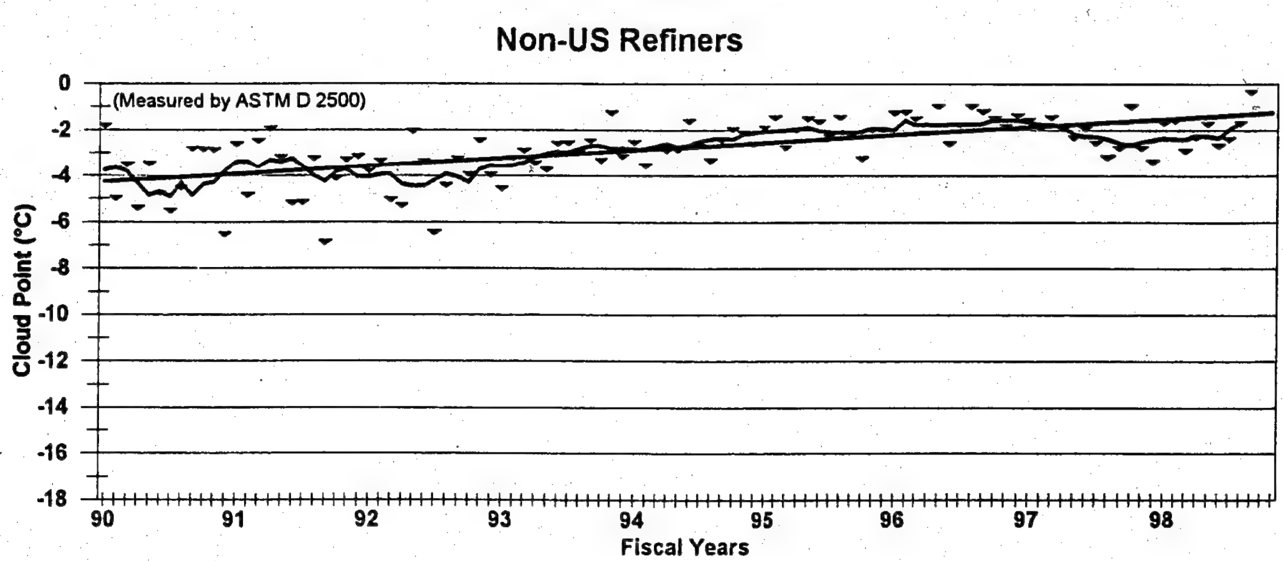




Cetane Index of F-76, FY 90-98



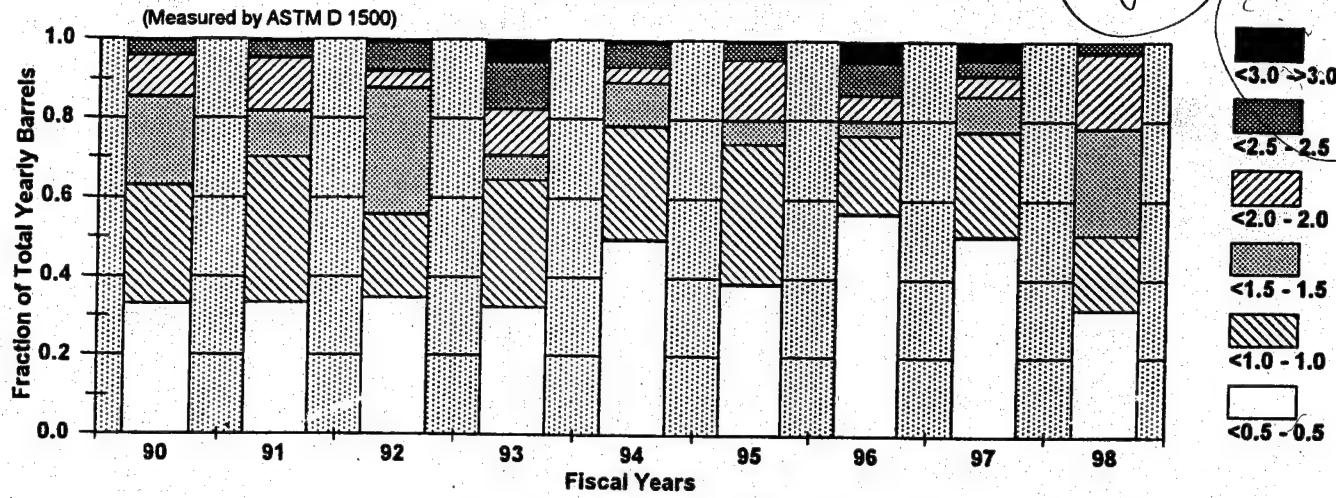




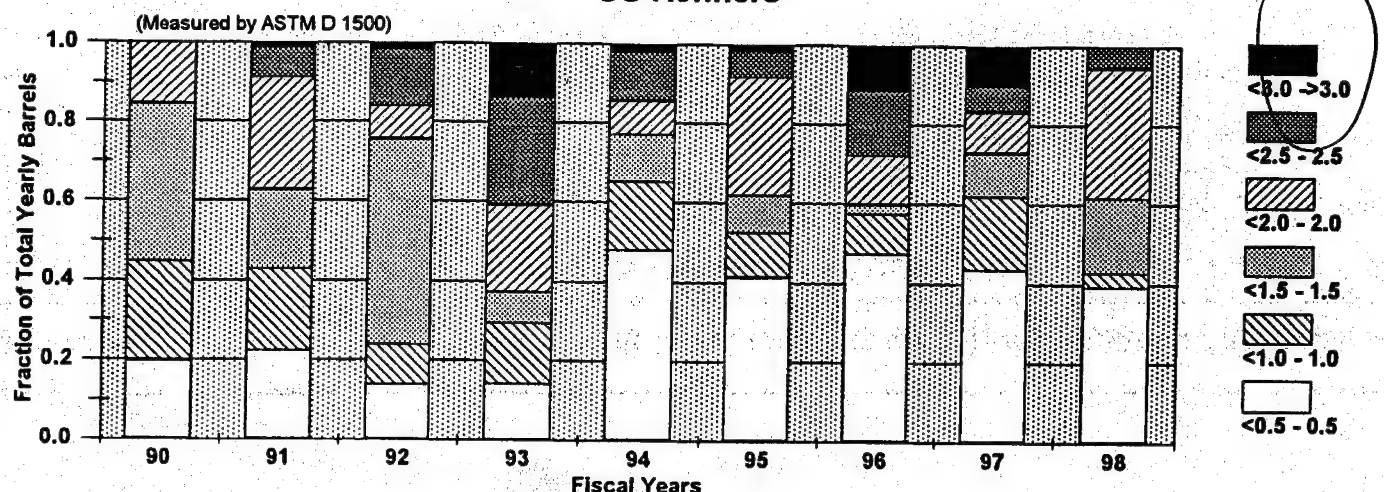
Cloud Point of F-76, FY 90-98

What is this ?

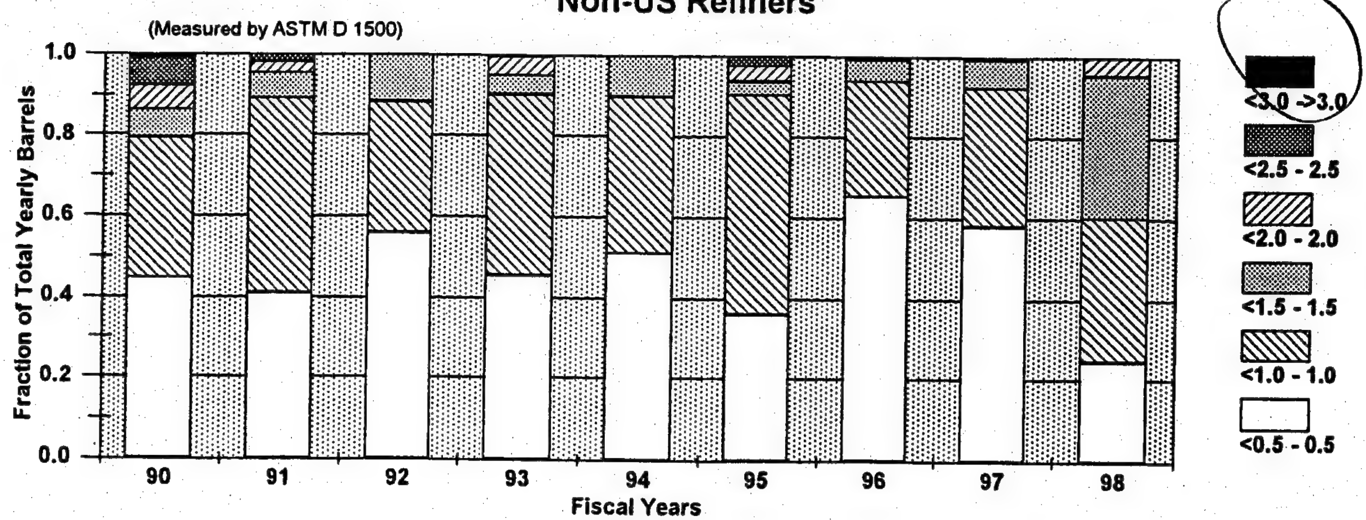
All Refiners Worldwide



US Refiners

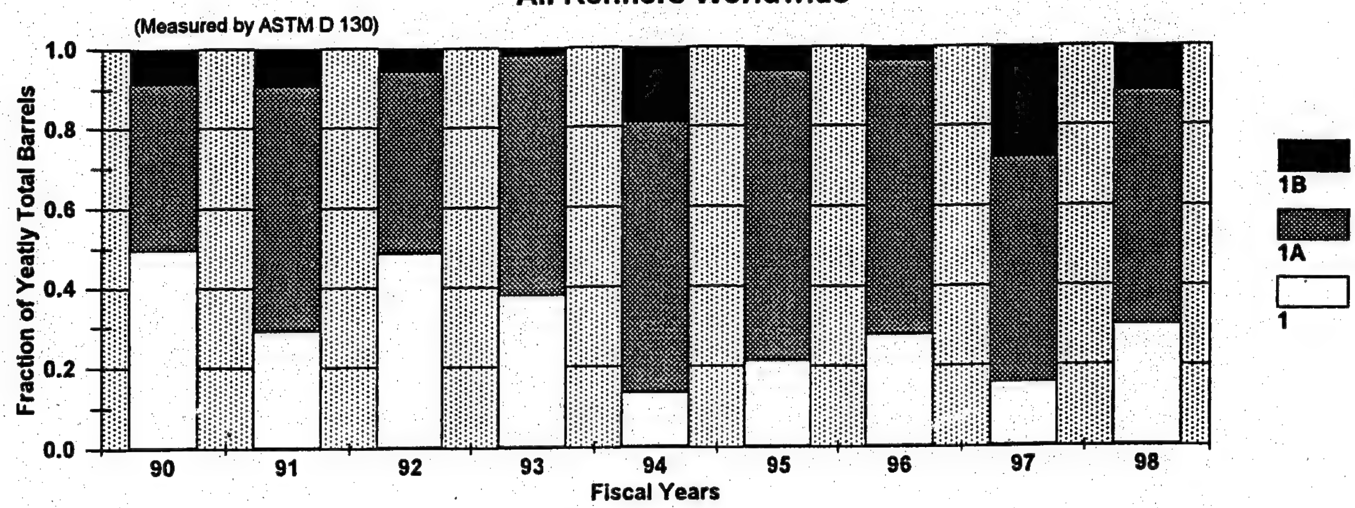


Non-US Refiners

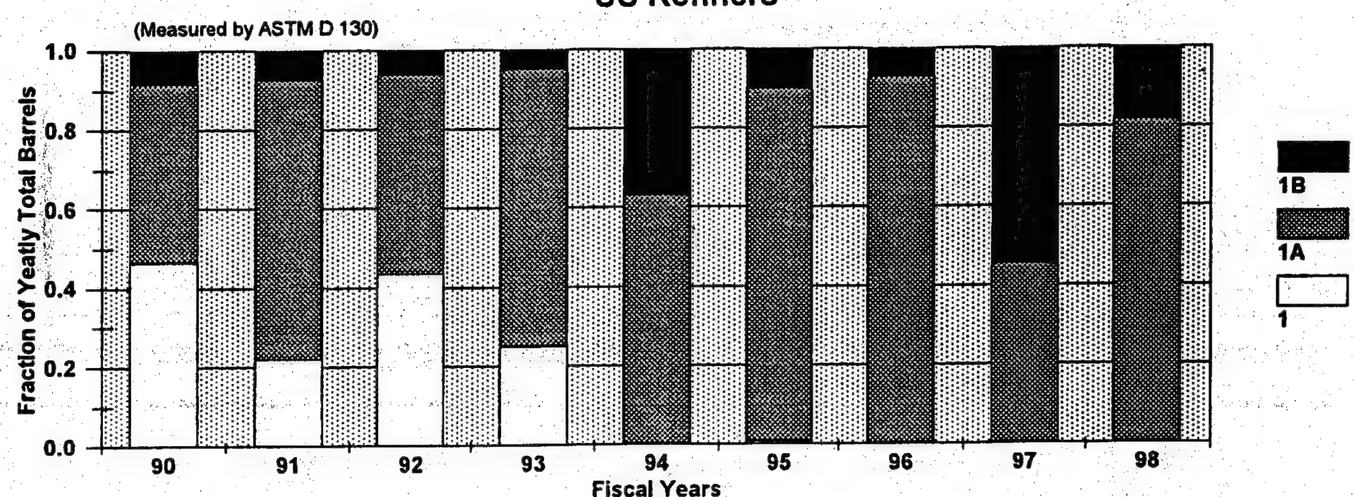


Color of F-76, FY 90-98

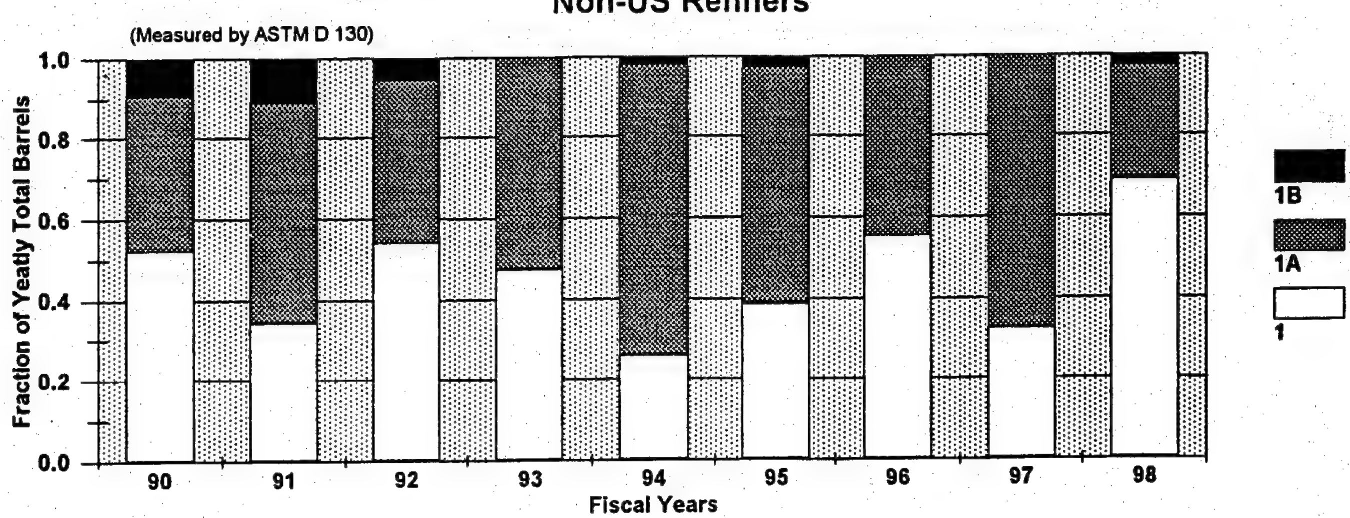
All Refiners Worldwide



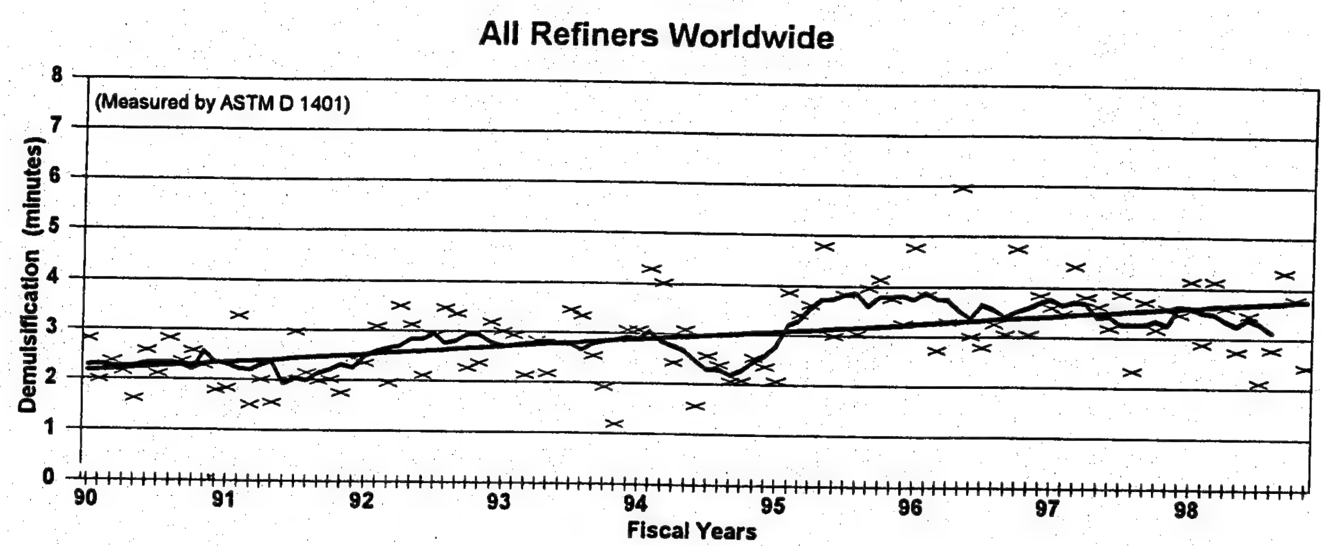
US Refiners

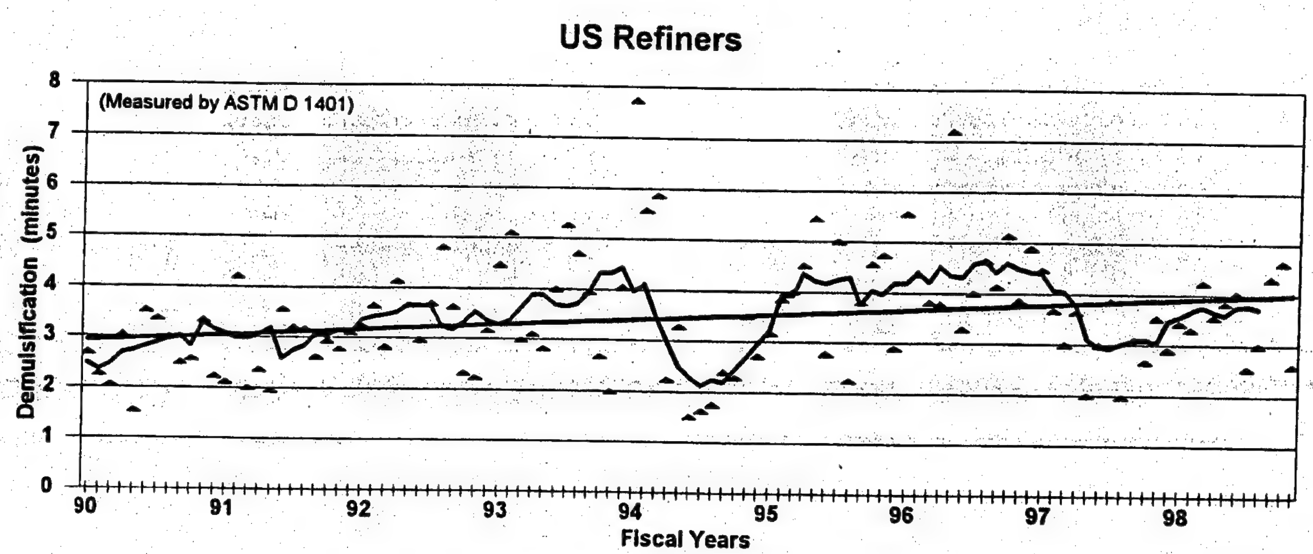


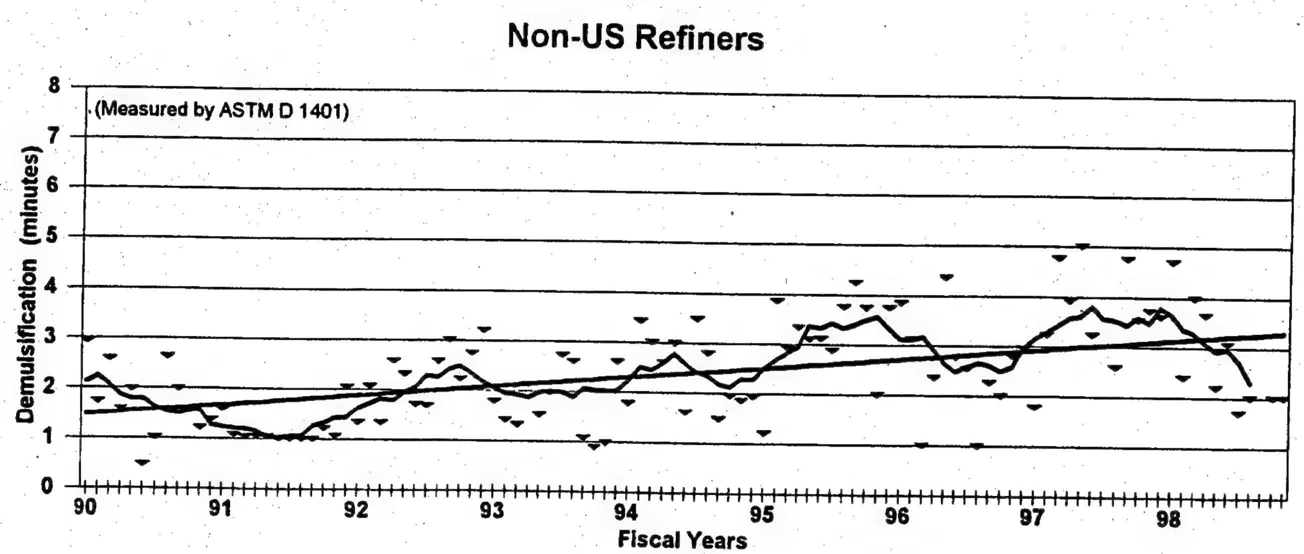
Non-US Refiners



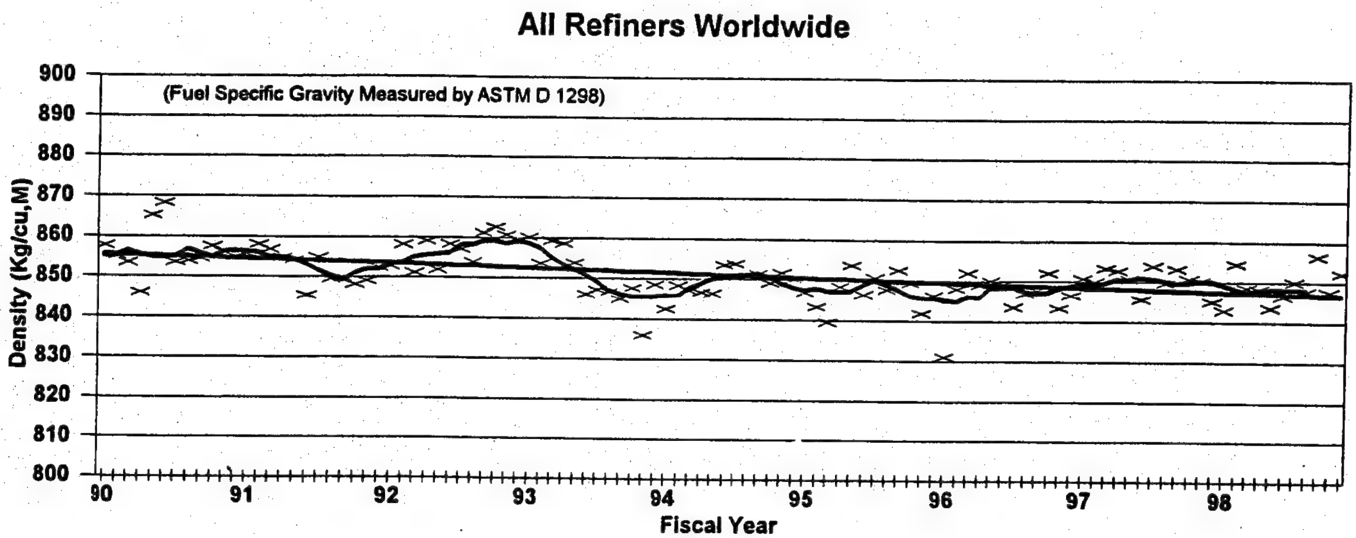
Copper Corrosion of F-76, FY 90-98

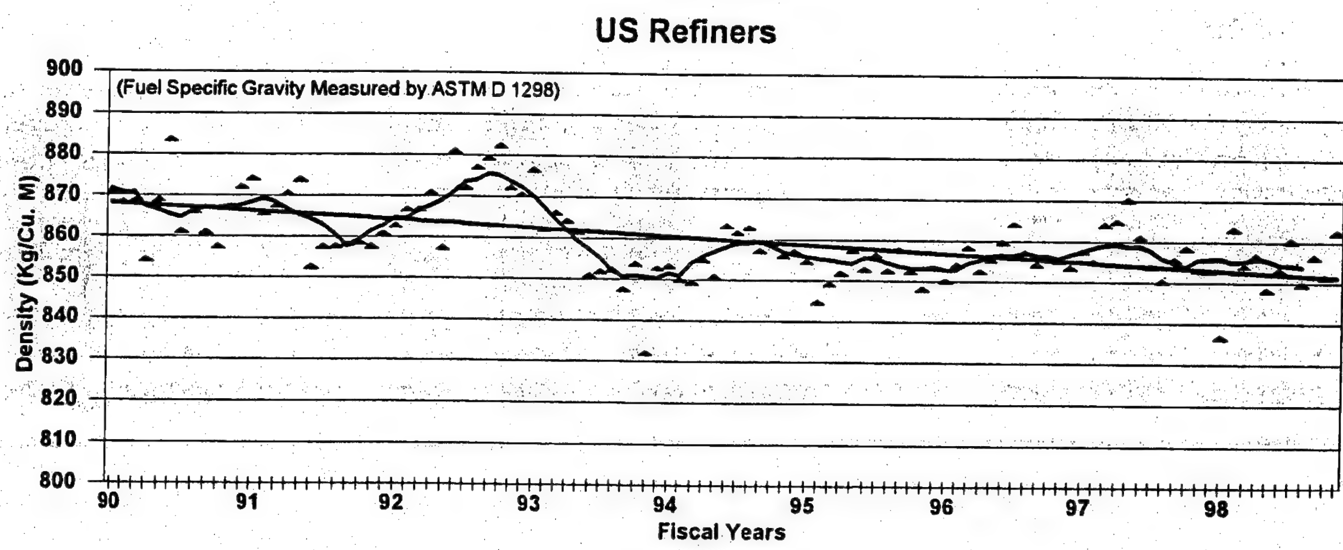


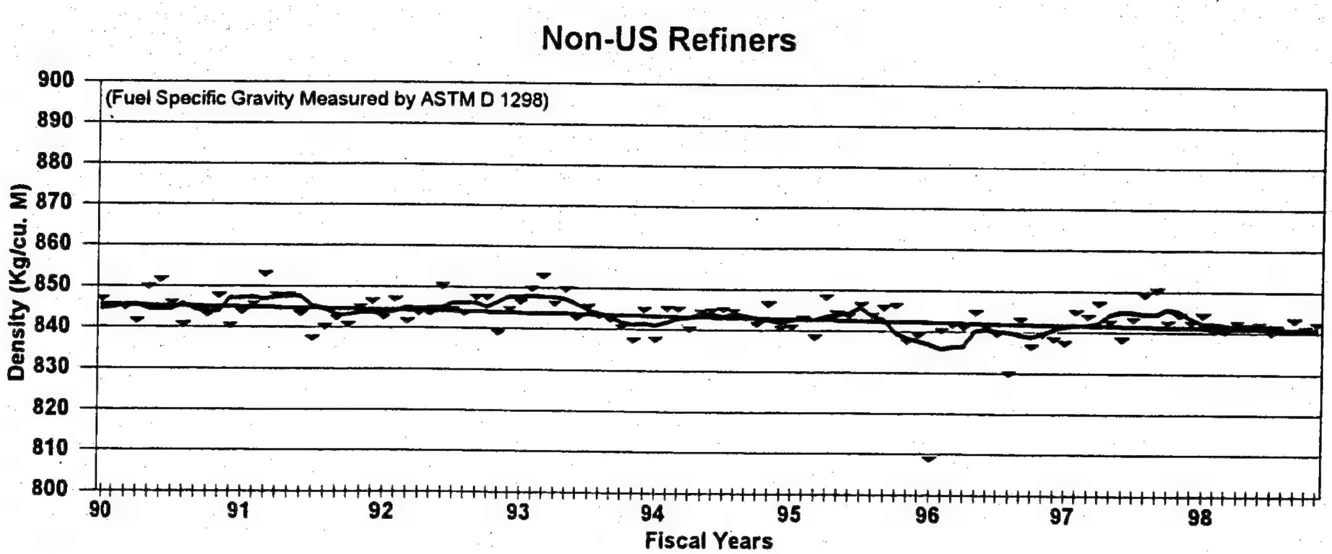




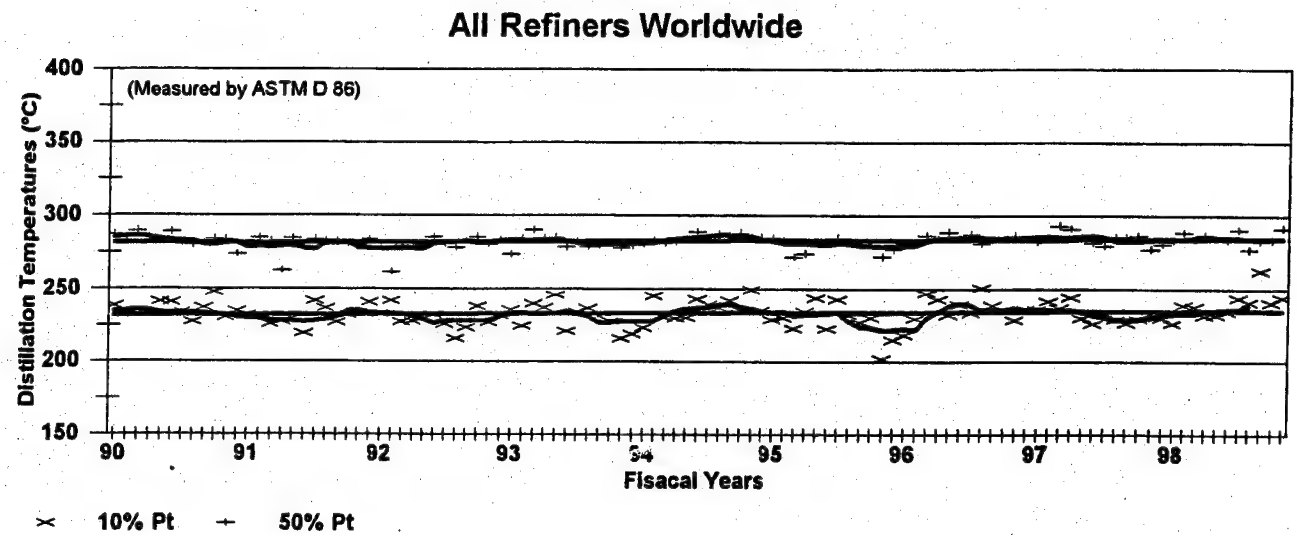
Demulsification Time of F-76, FY 90-98

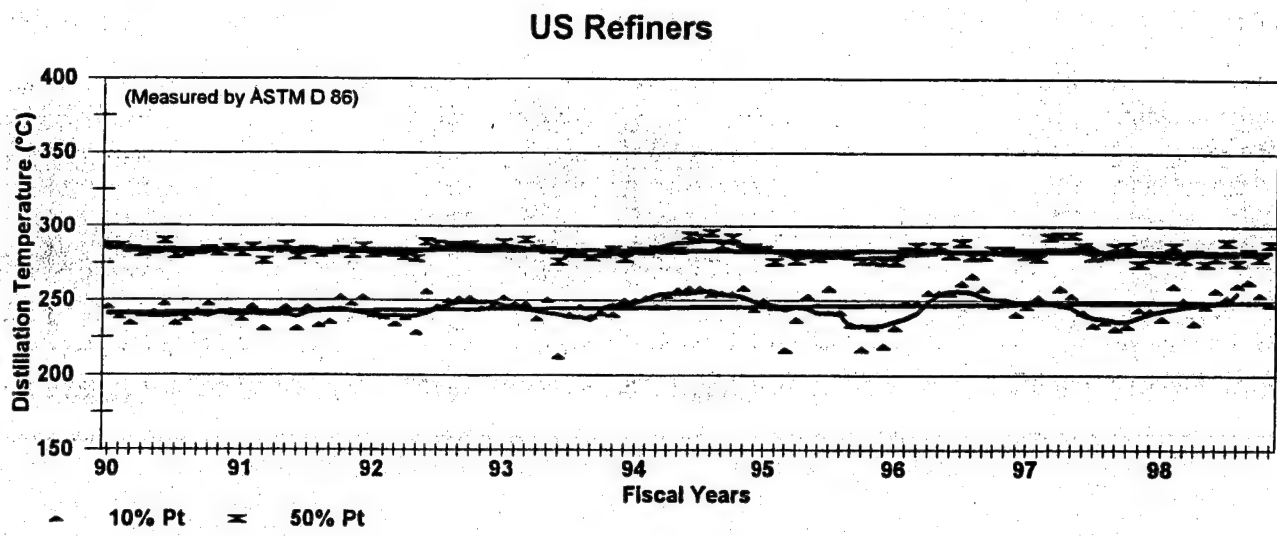


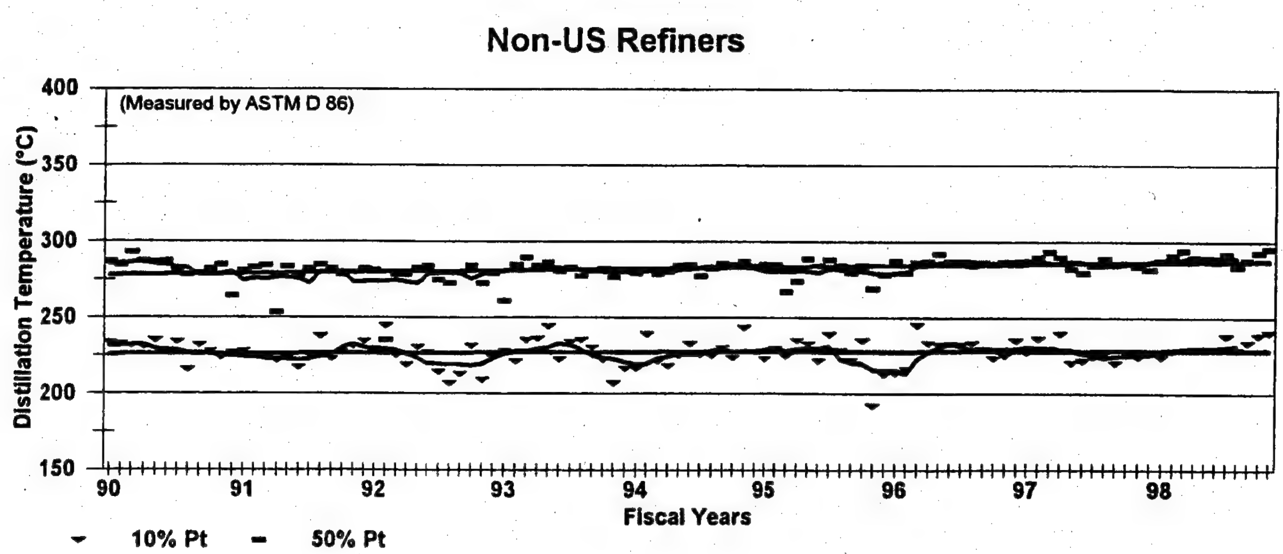




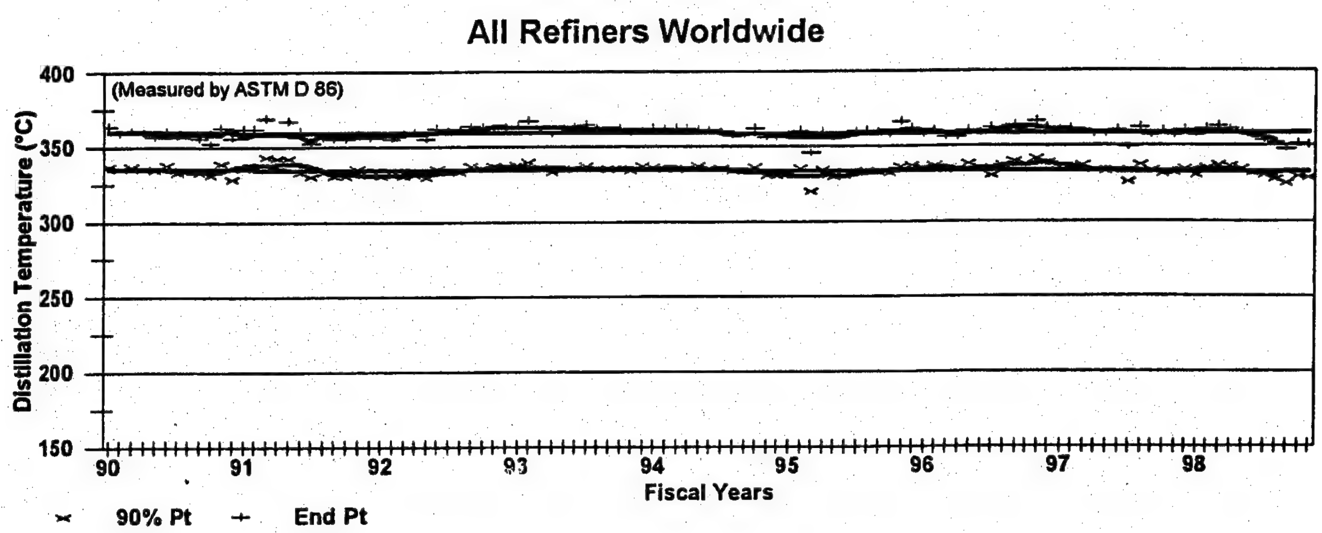
Density of F-76, FY 90-98

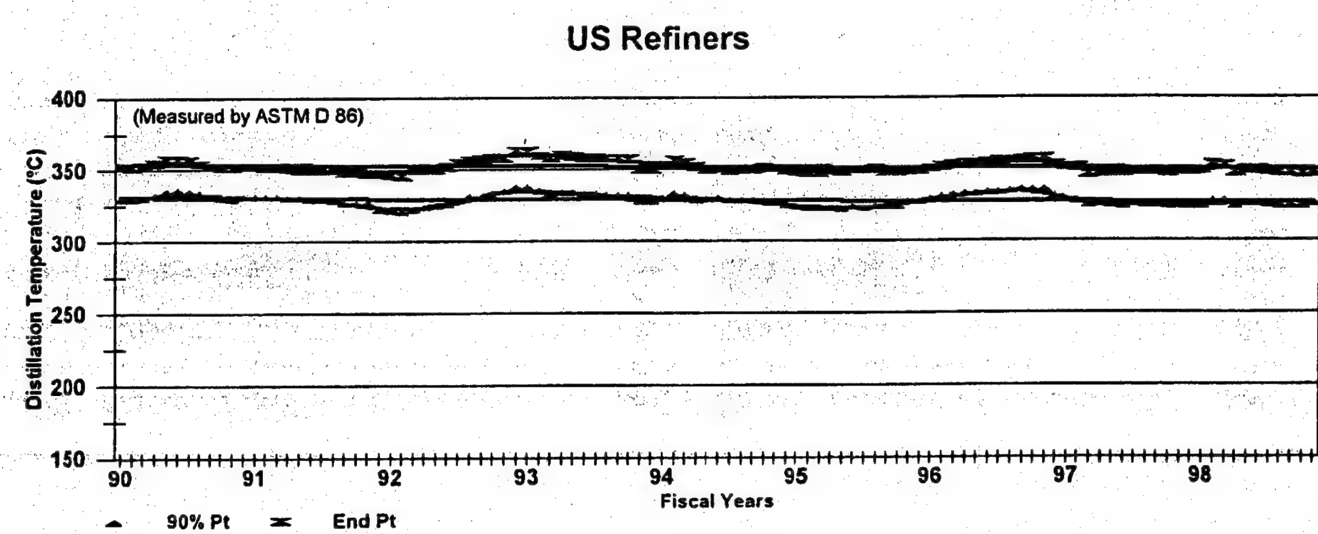


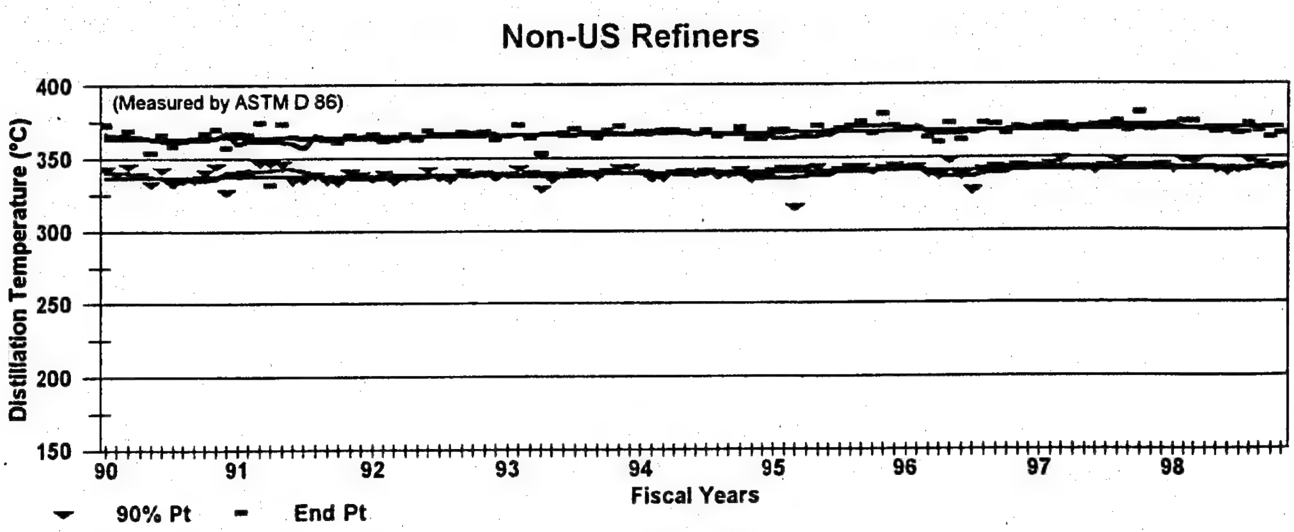




Distillation 10% Point and 50% Point of F-76, FY 90-98

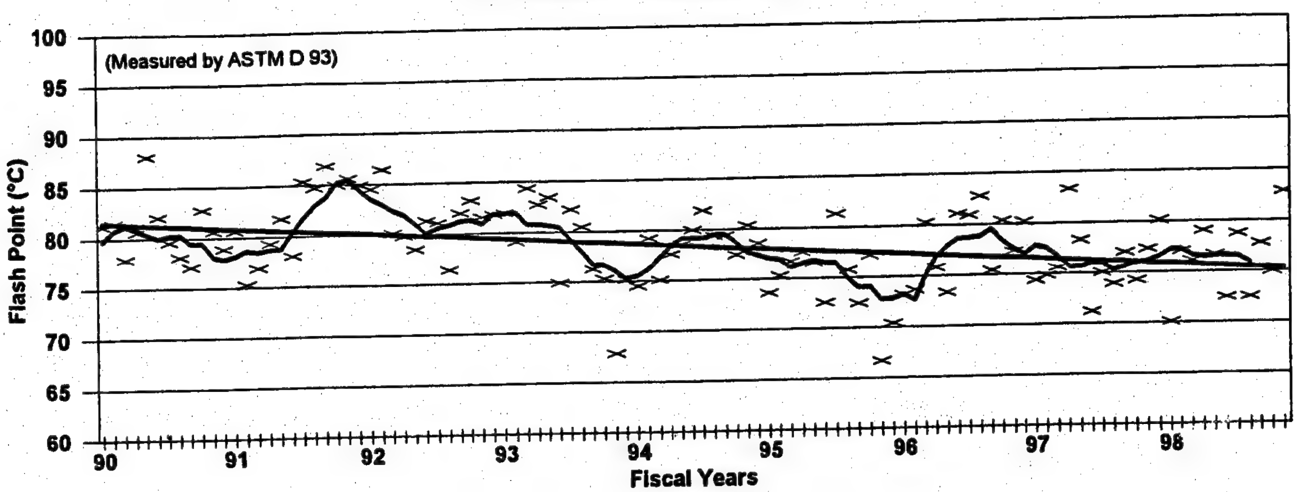




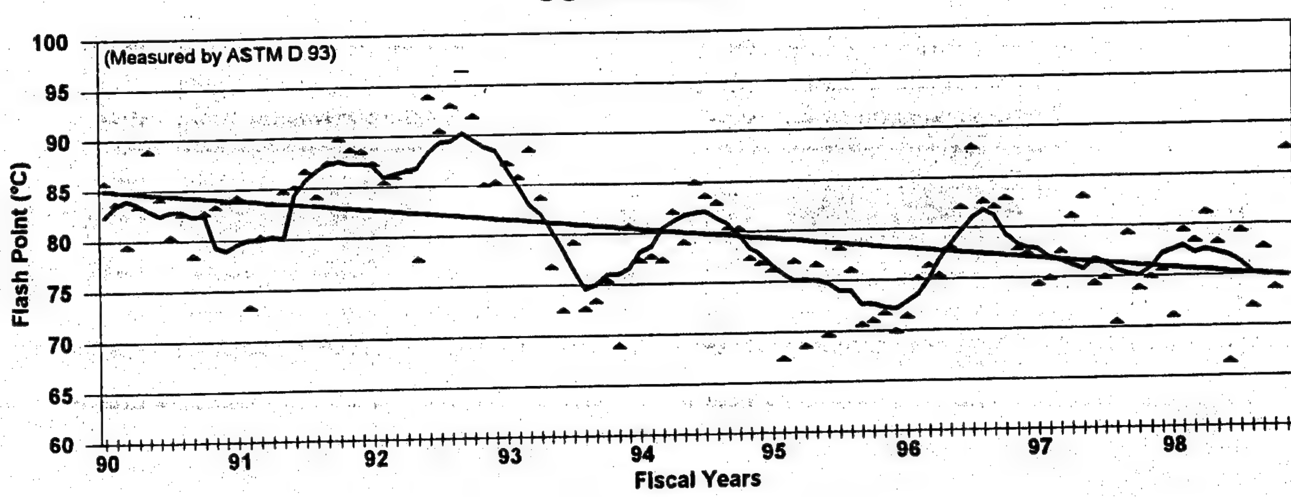


Distillation 90% Point and End Point of F-76, FY 90-98

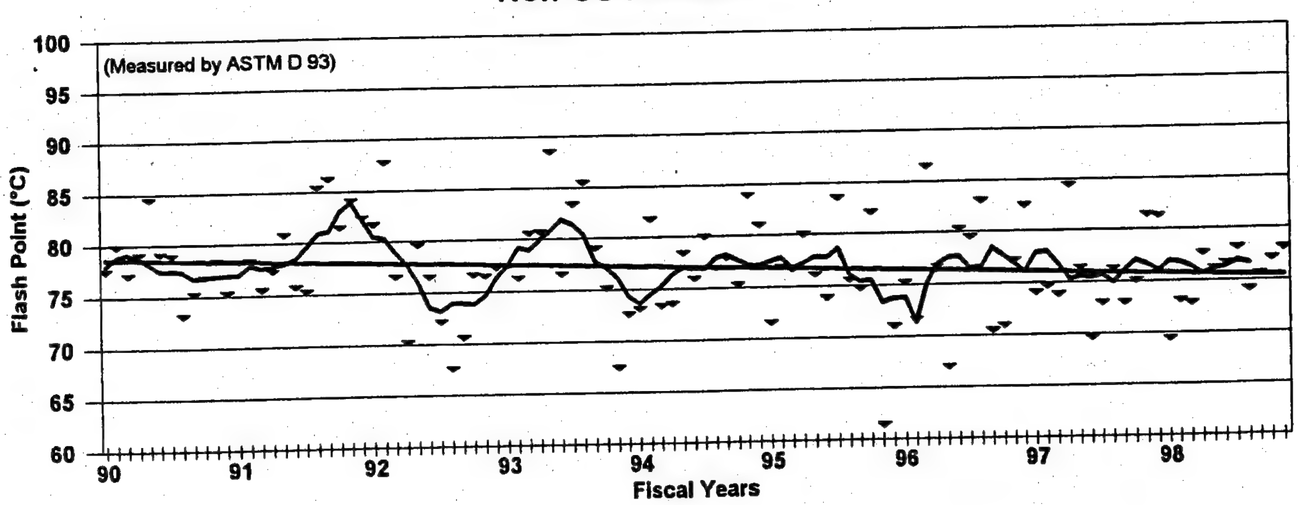
All Refiners Worldwide



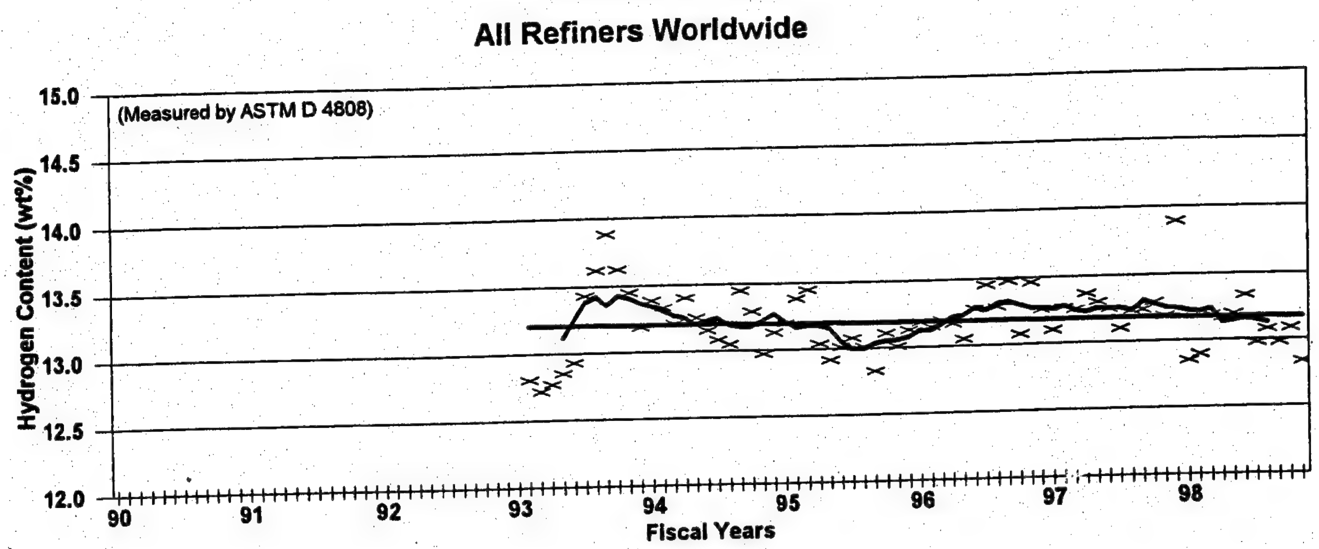
US Refiners

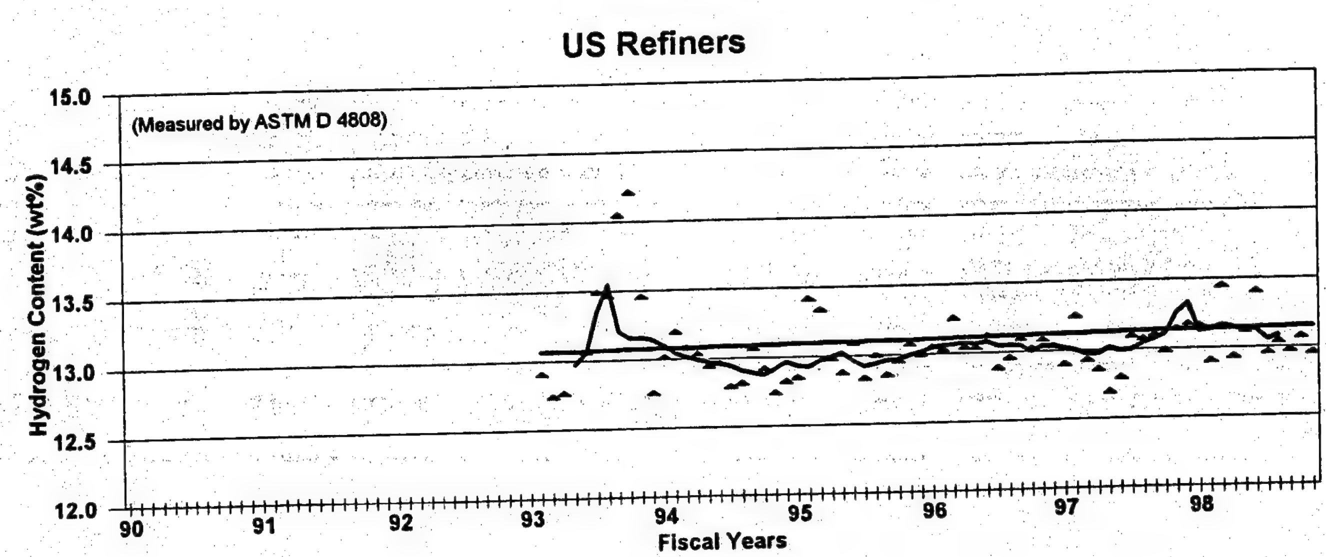


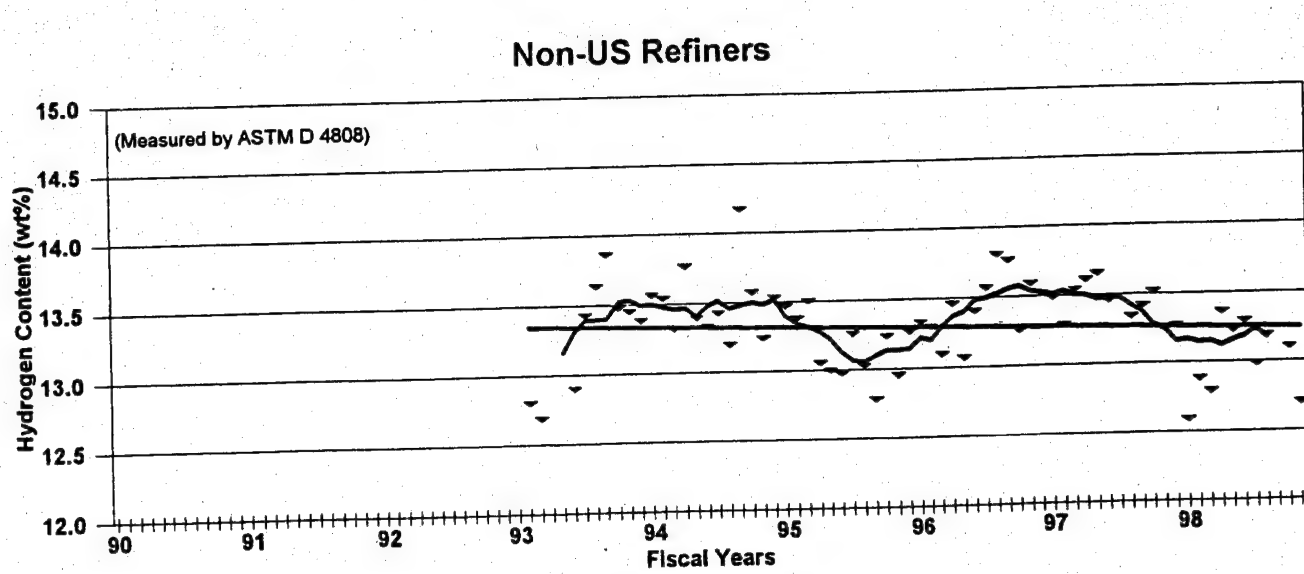
Non-US Refiners



Flash Point of F-76, FY 90-98

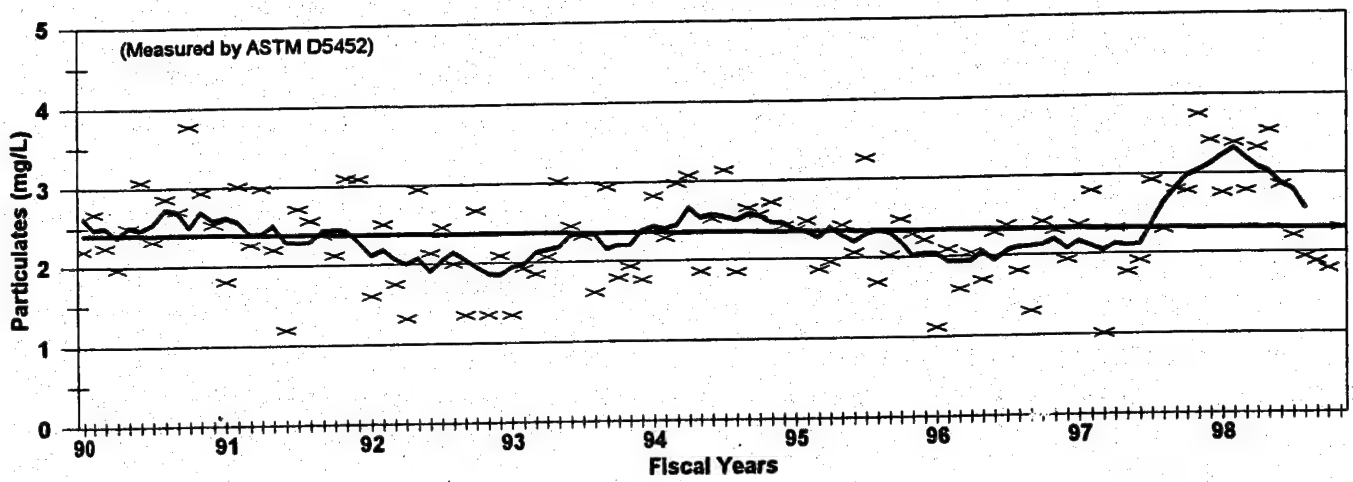




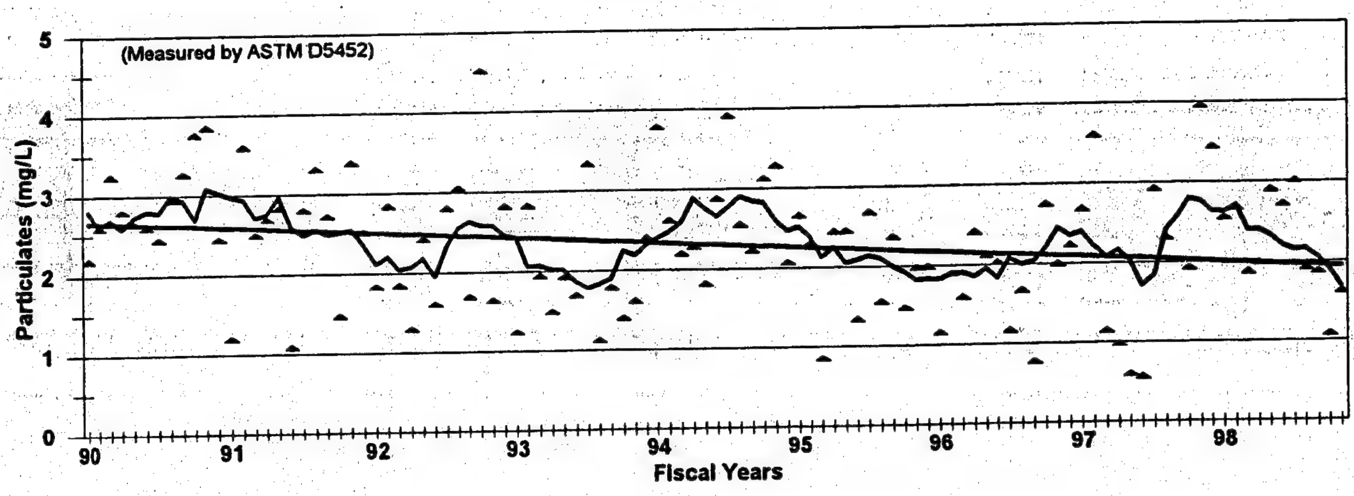


Hydrogen Content of F-76, FY 90-98

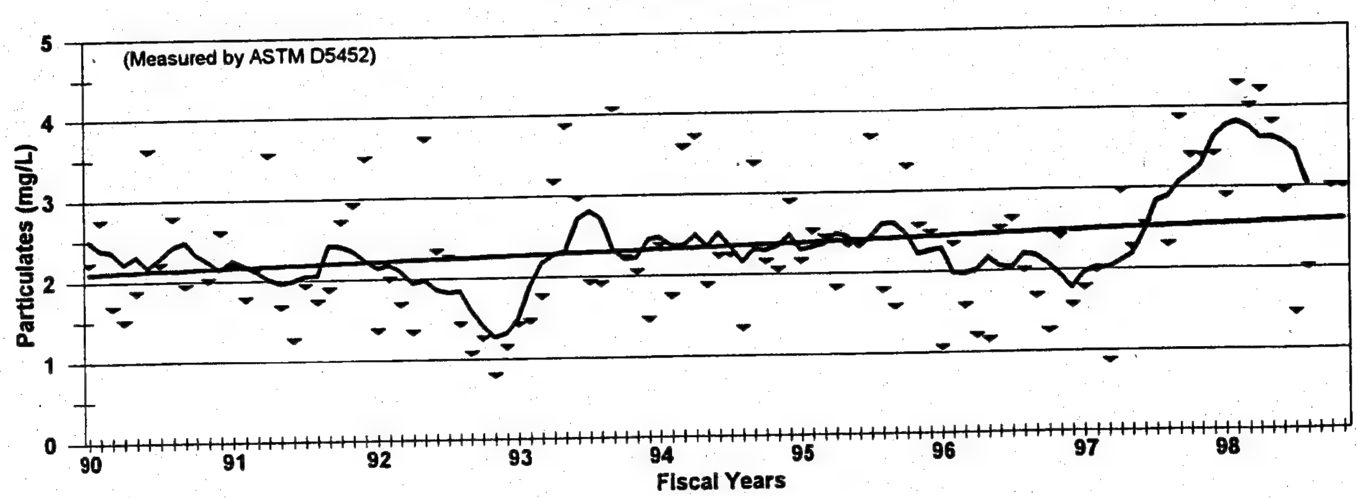
All Refiners Worldwide



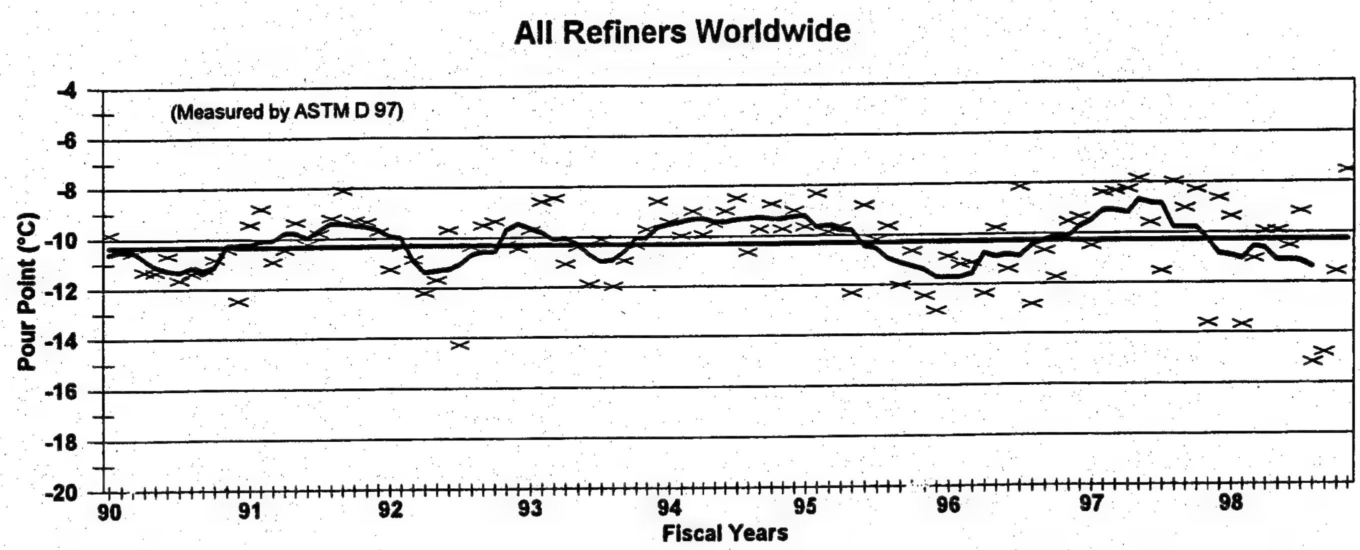
US Refiners

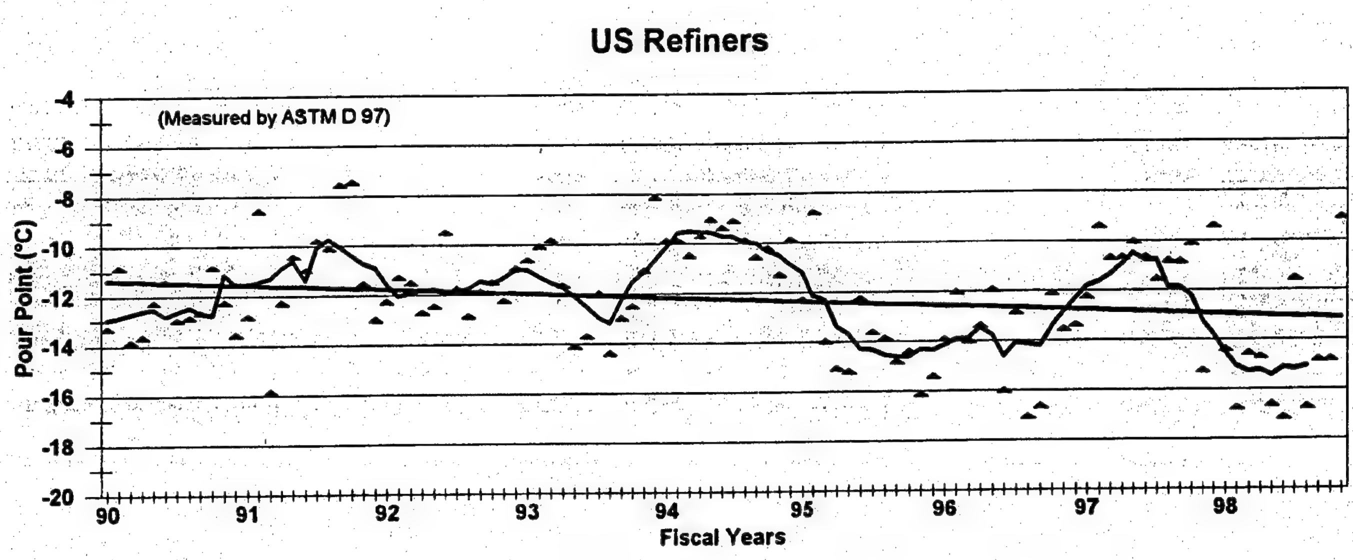


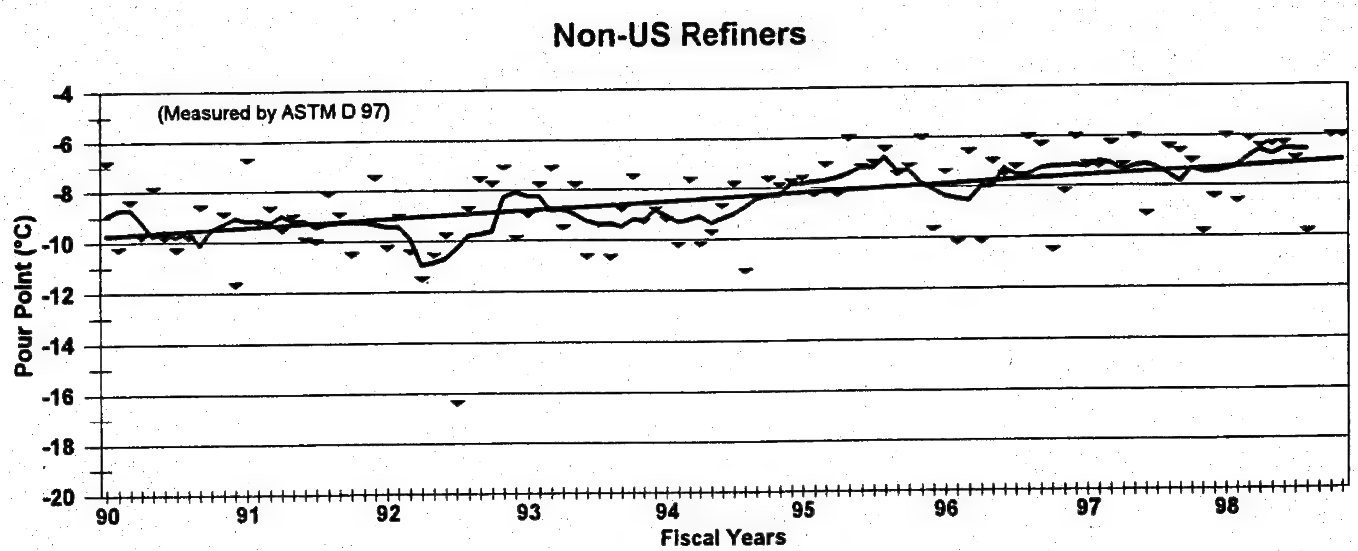
Non-US Refiners



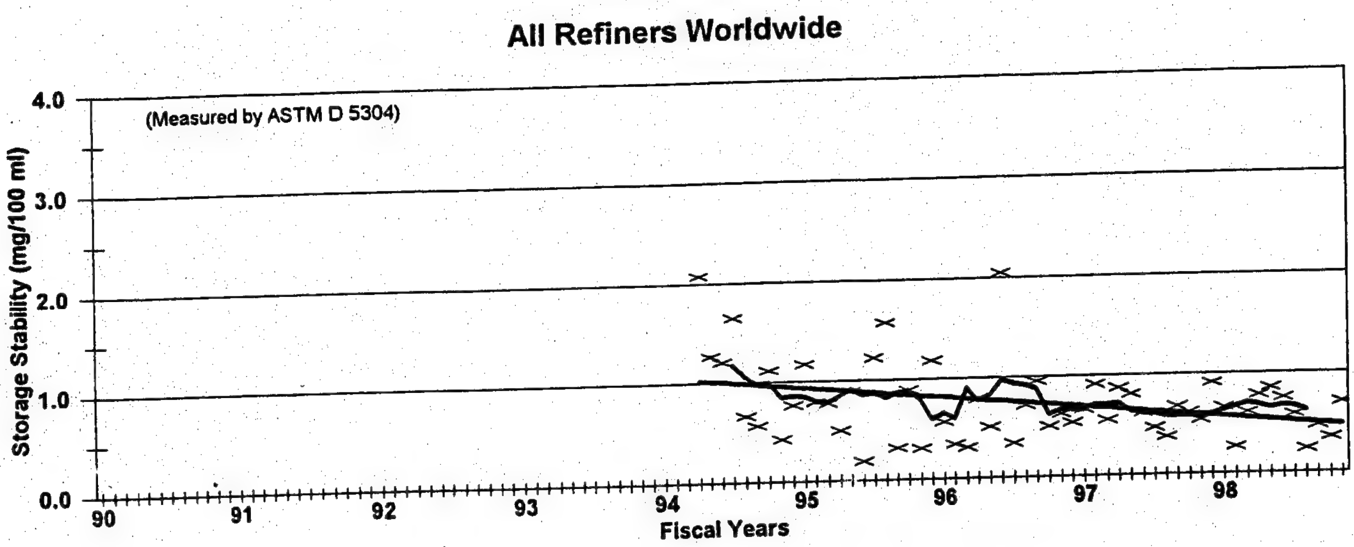
Particulate Contamination of F-76, FY 90-98

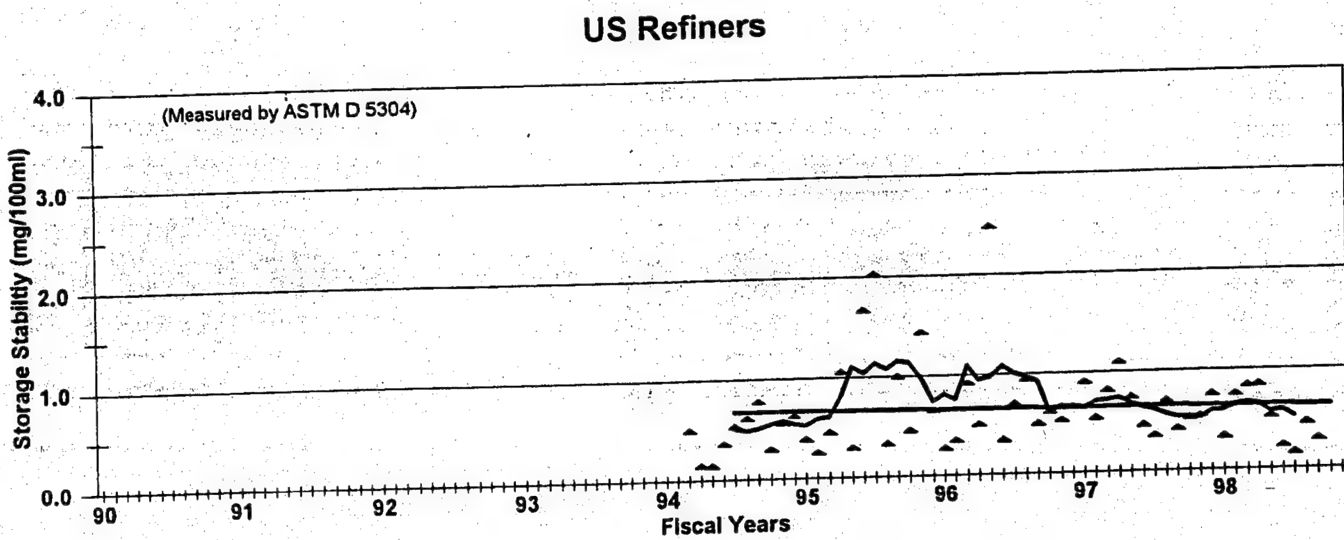


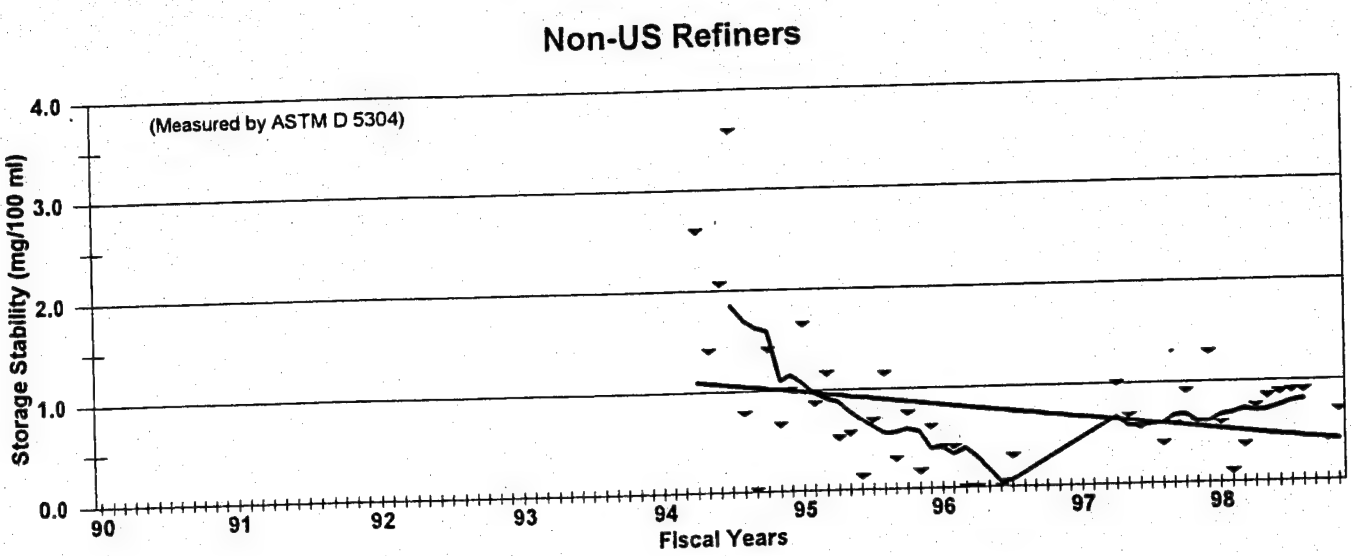




Pour Point of F-76, FY 90-98

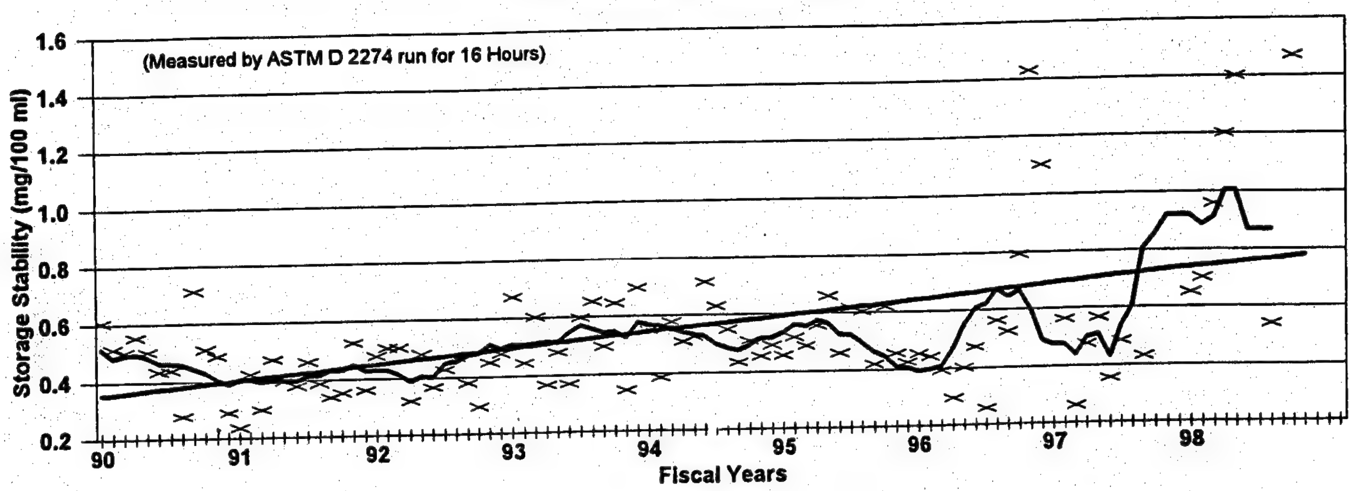




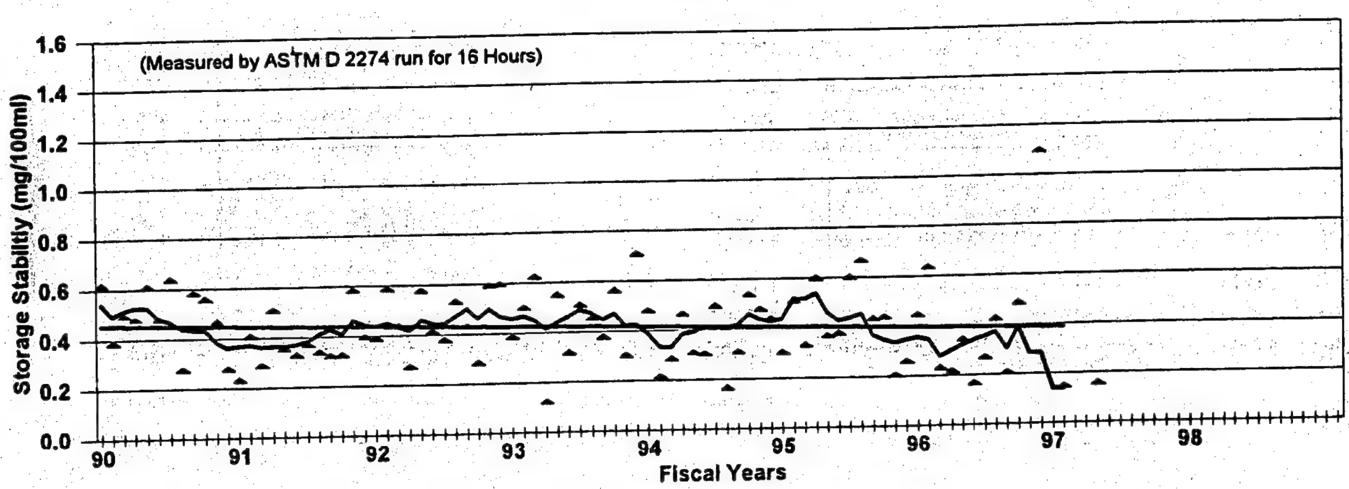


Storage Stability of F-76, FY 90-98

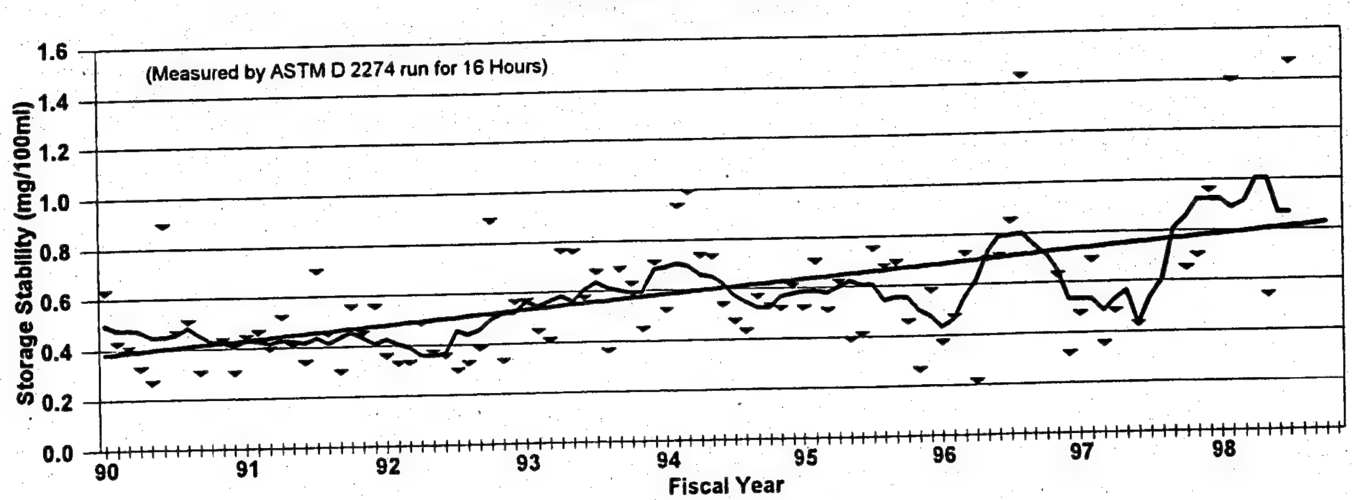
All Refiners Worldwide



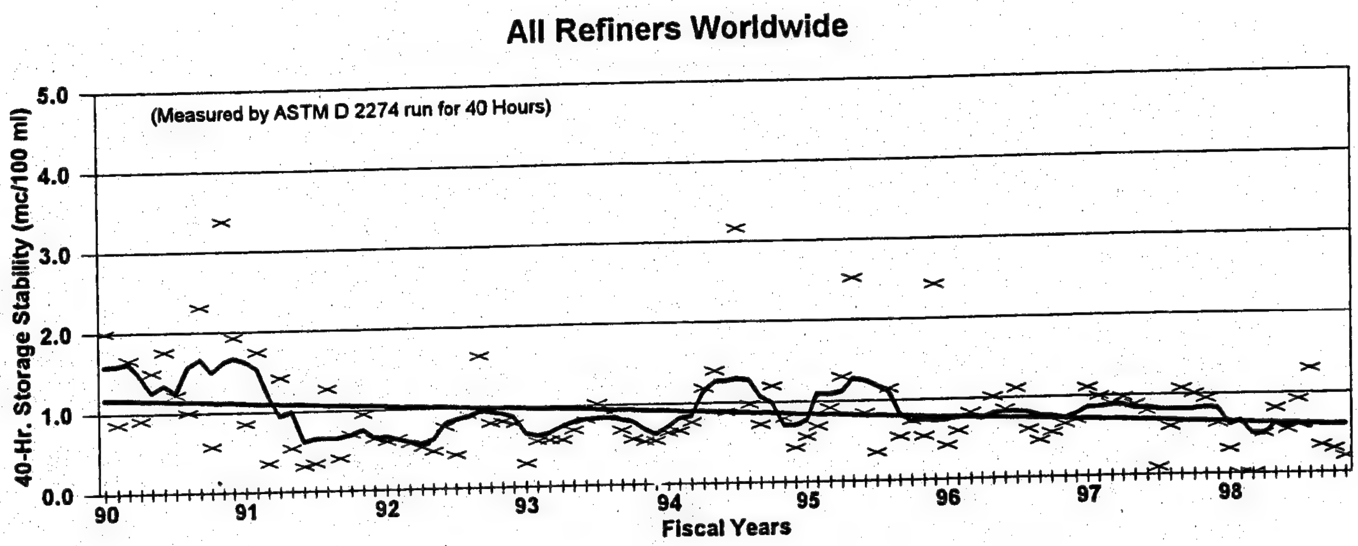
US Refiners

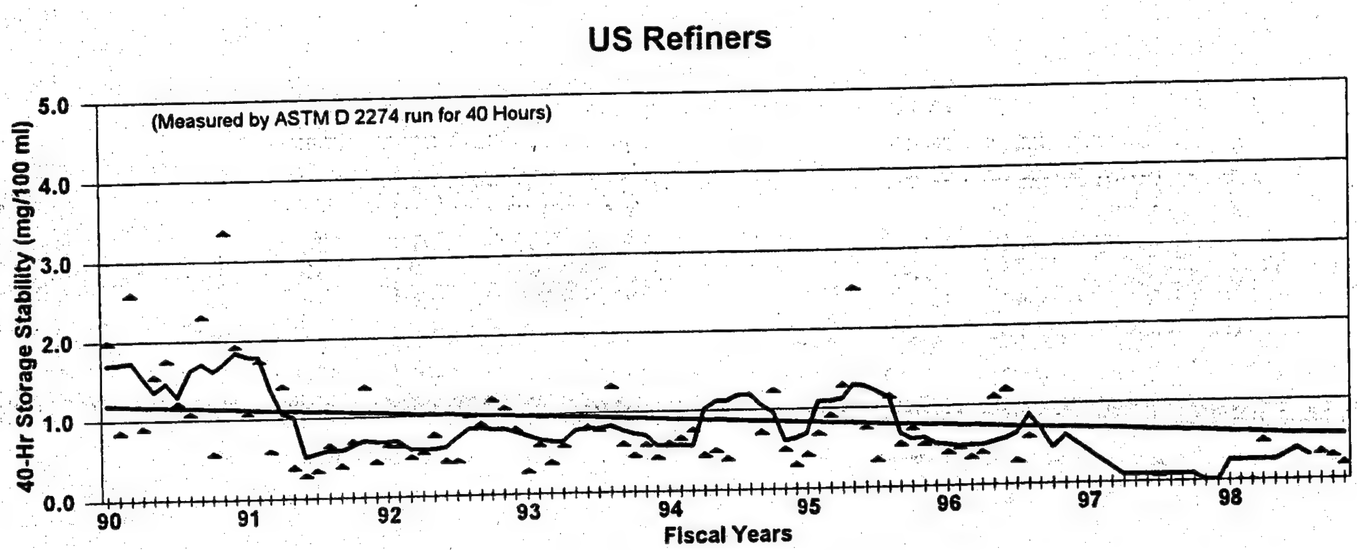


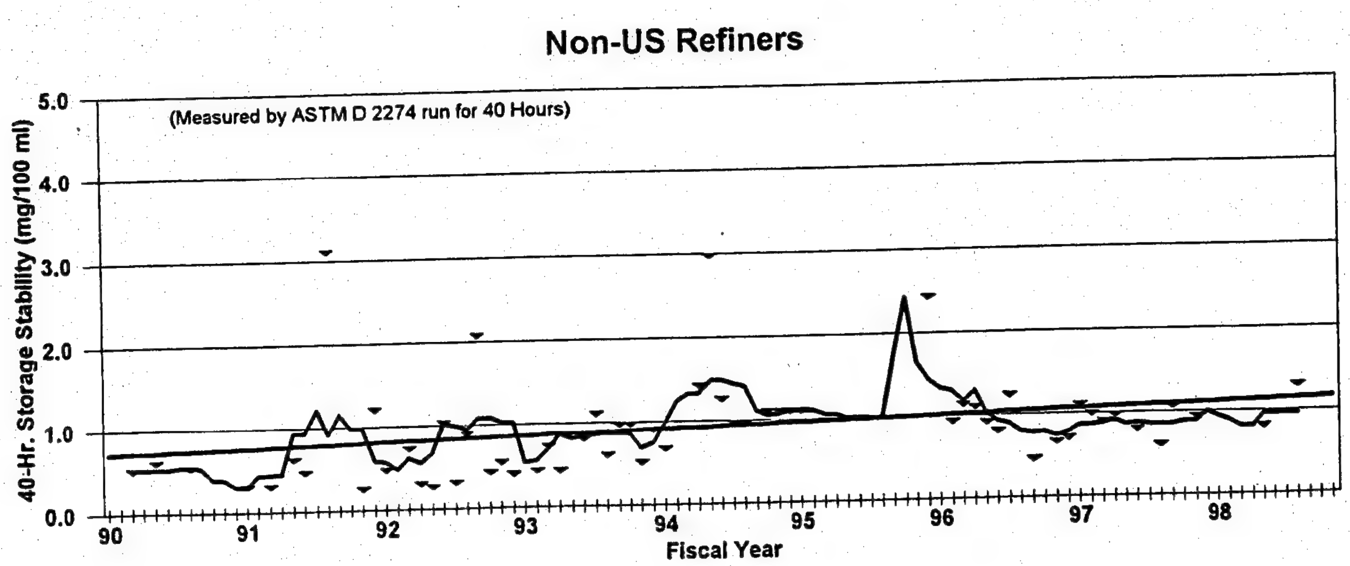
Non-US Refiners



Storage Stability of F-76, FY 90-98

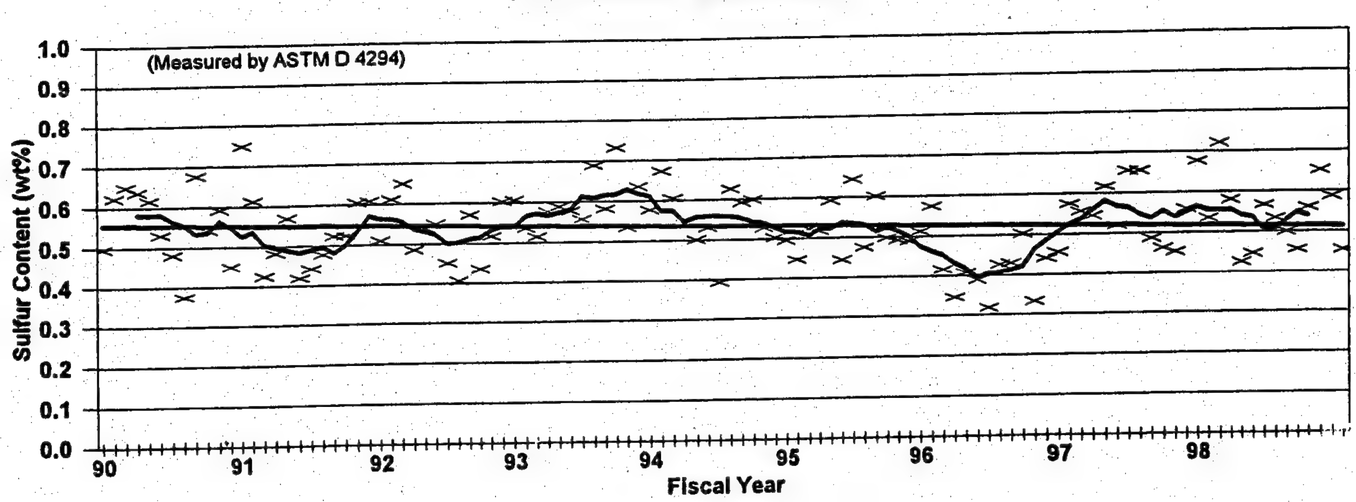




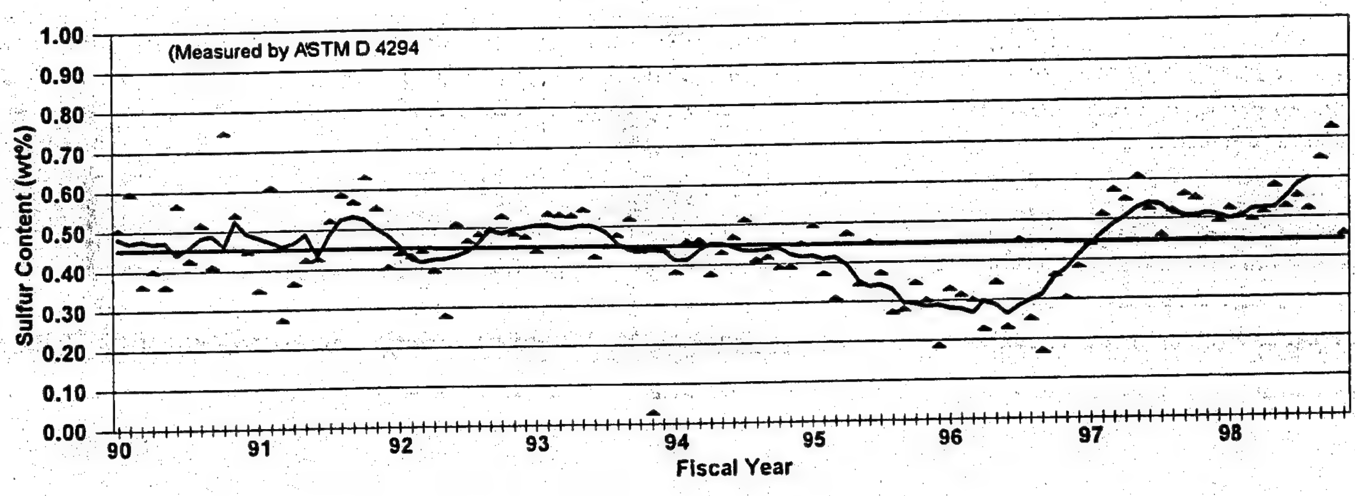


Storage Stability of F-76, FY 90-98

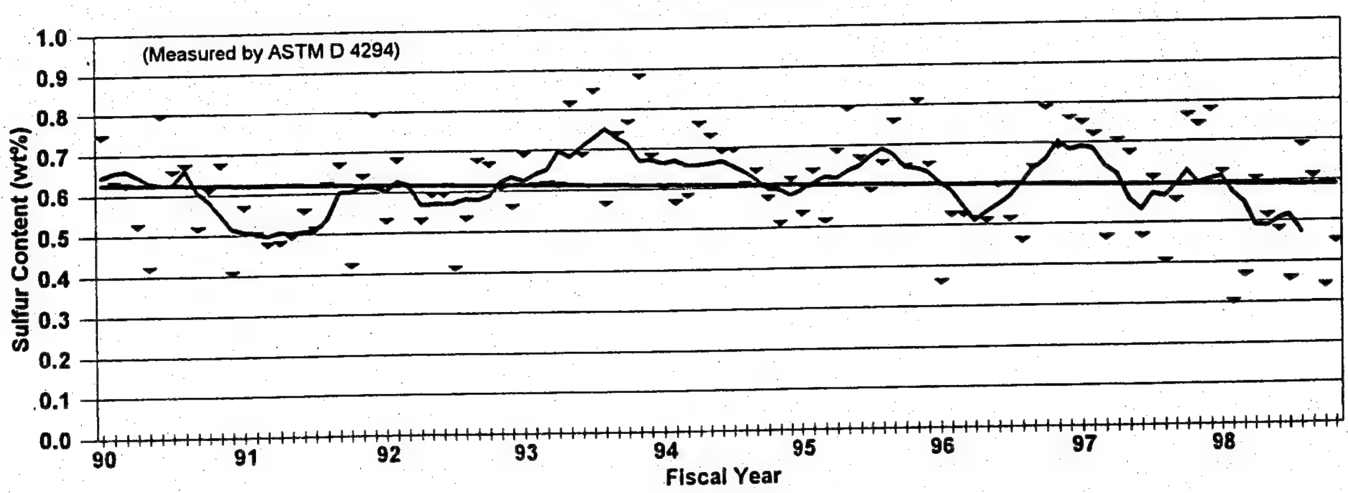
All Refiners Worldwide



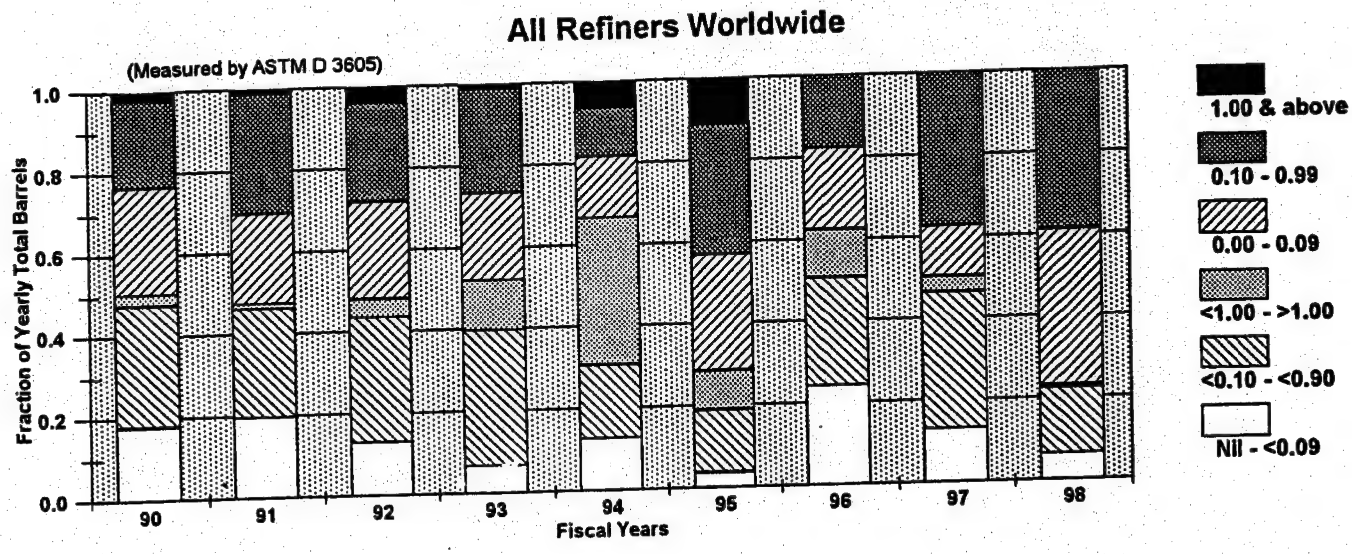
US Refiners

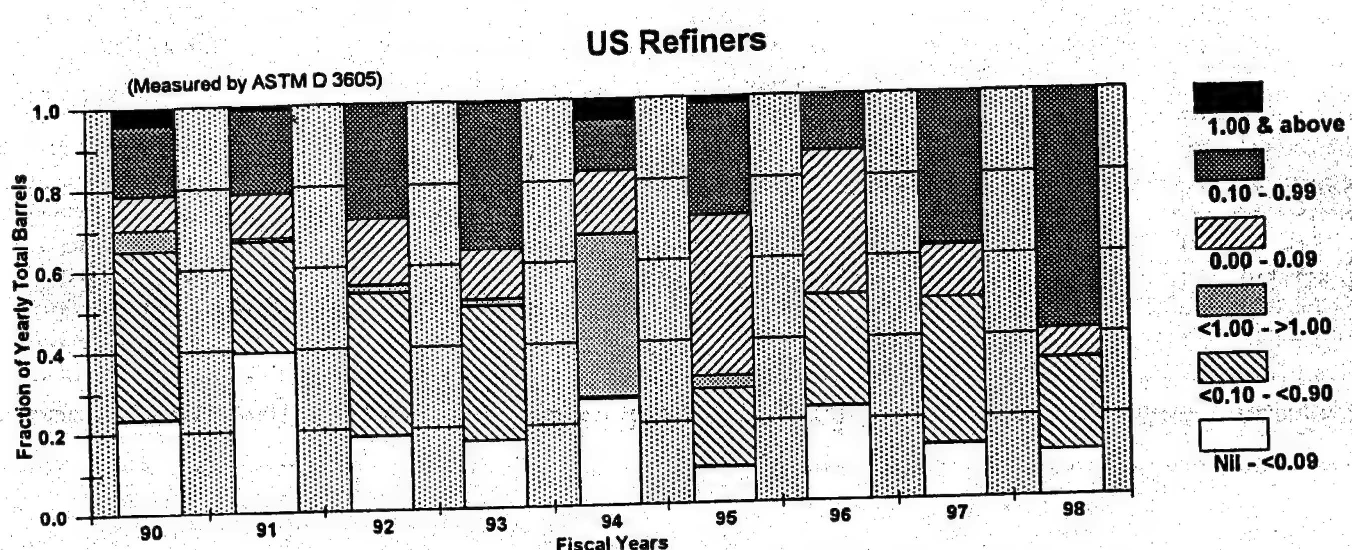


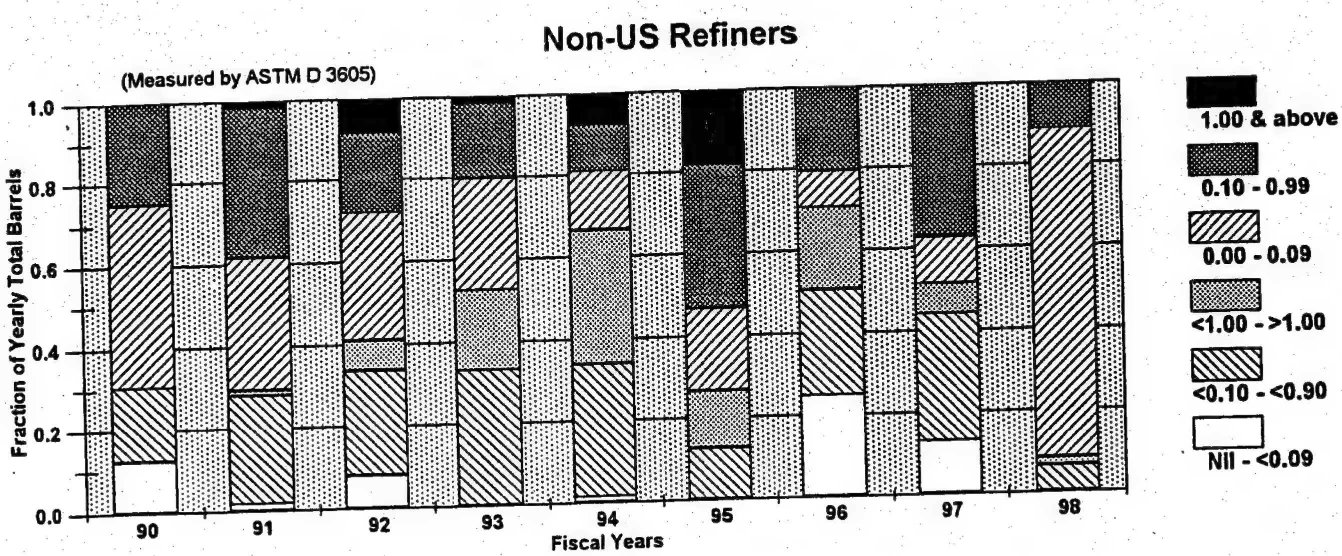
Non-US Refiners



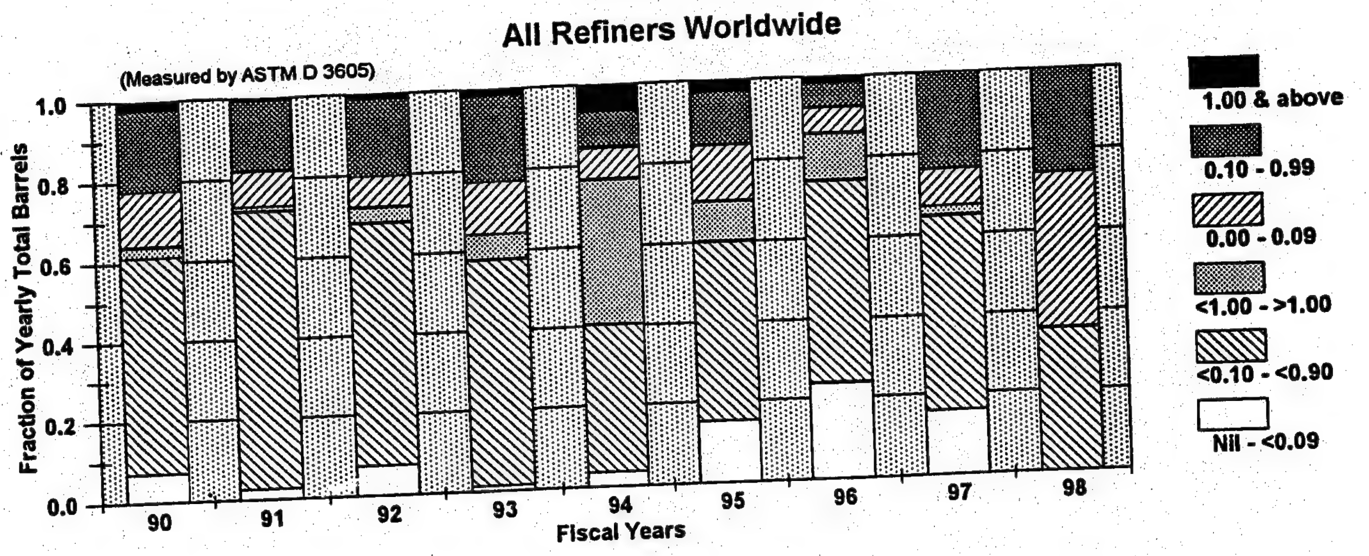
Sulfur Content of F-76, FY 90-98

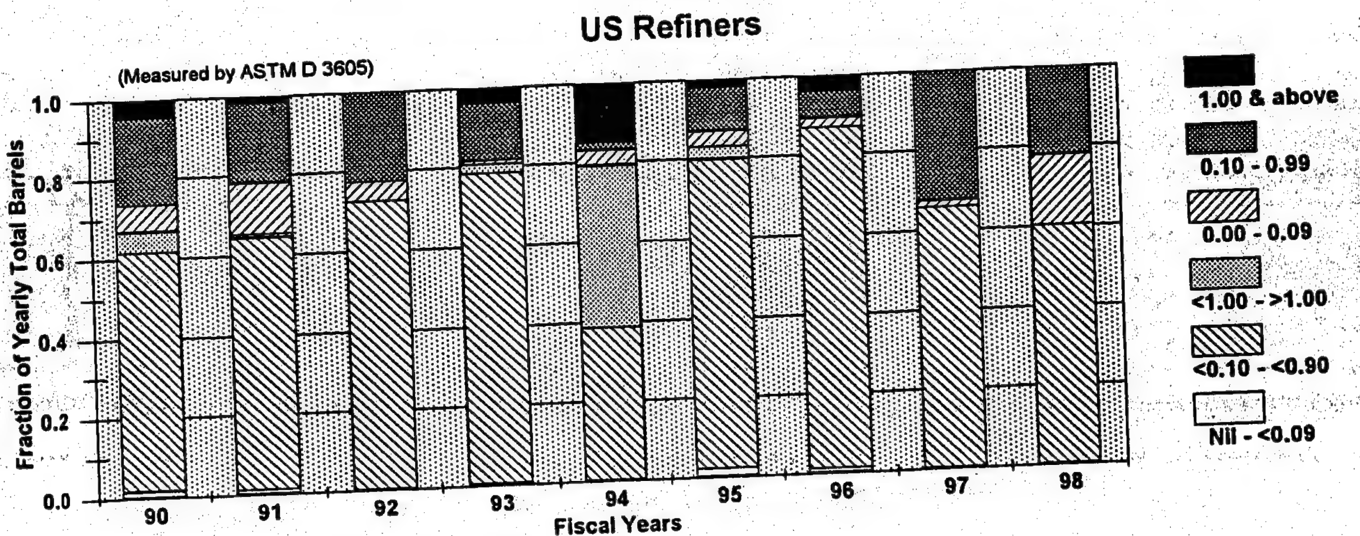


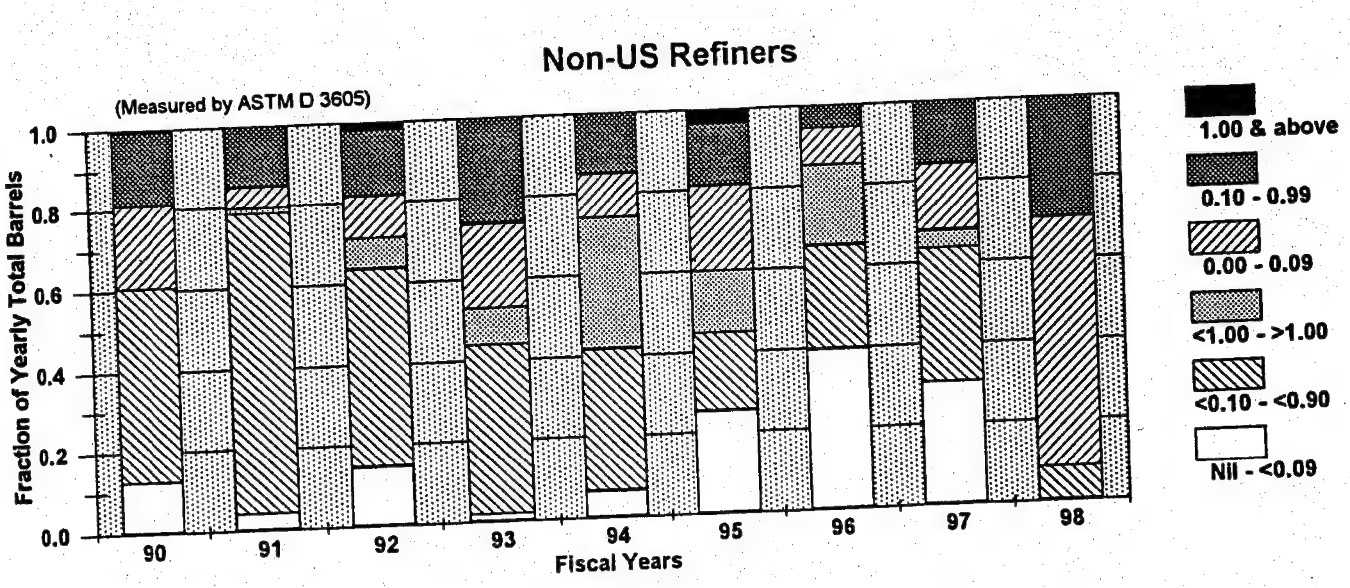




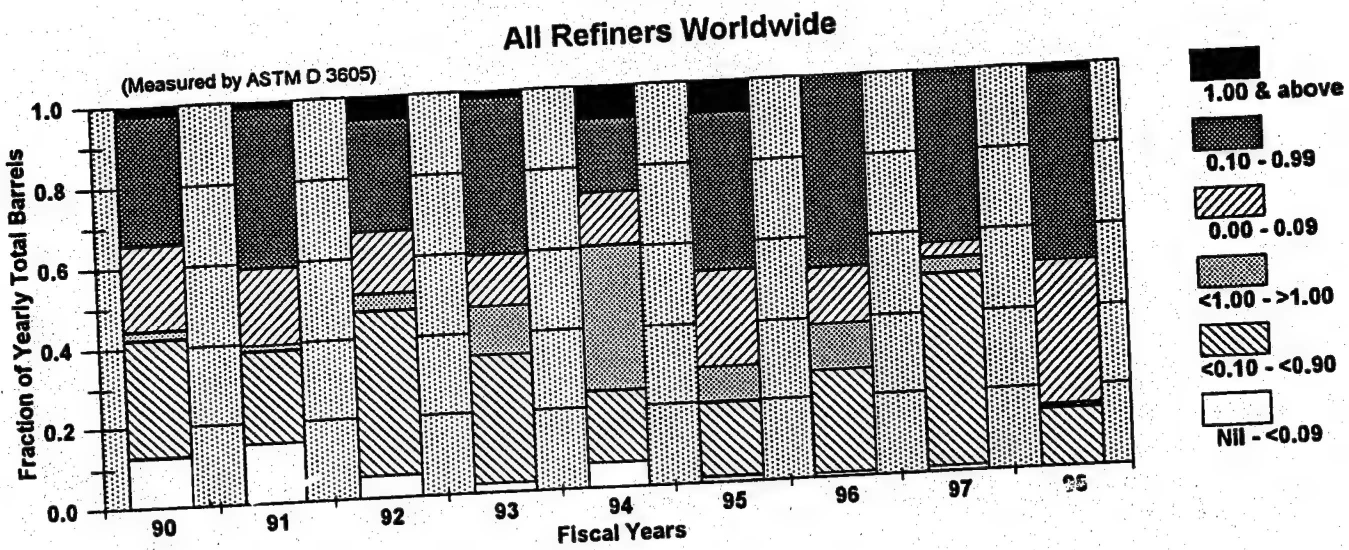
Trace Metals - Calcium Content of F-76, FY 90-98

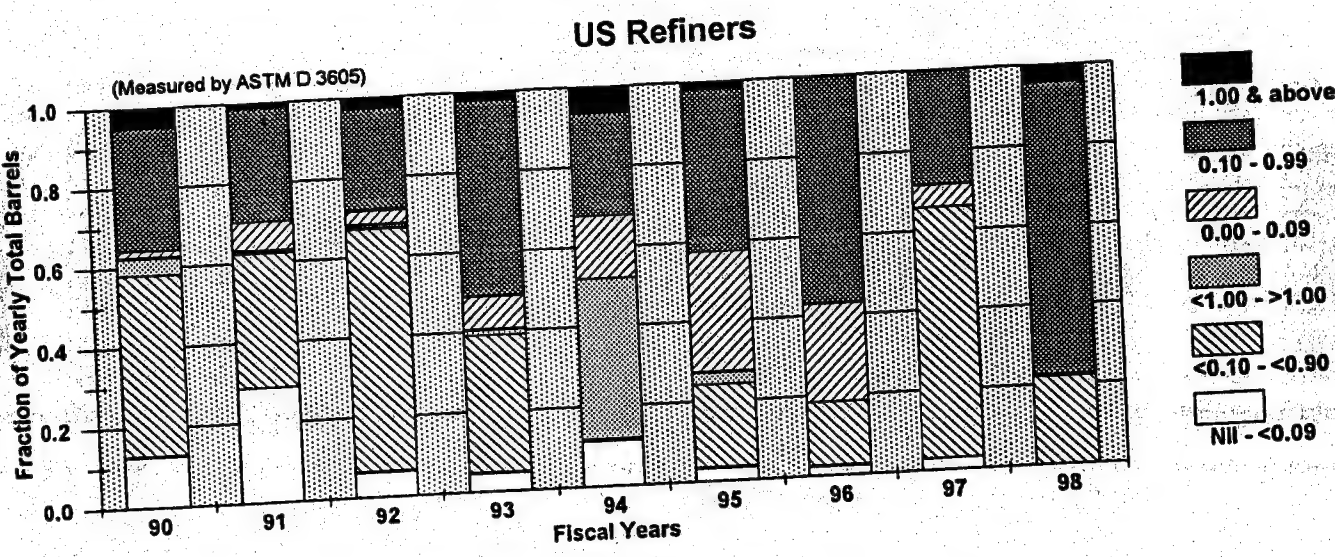


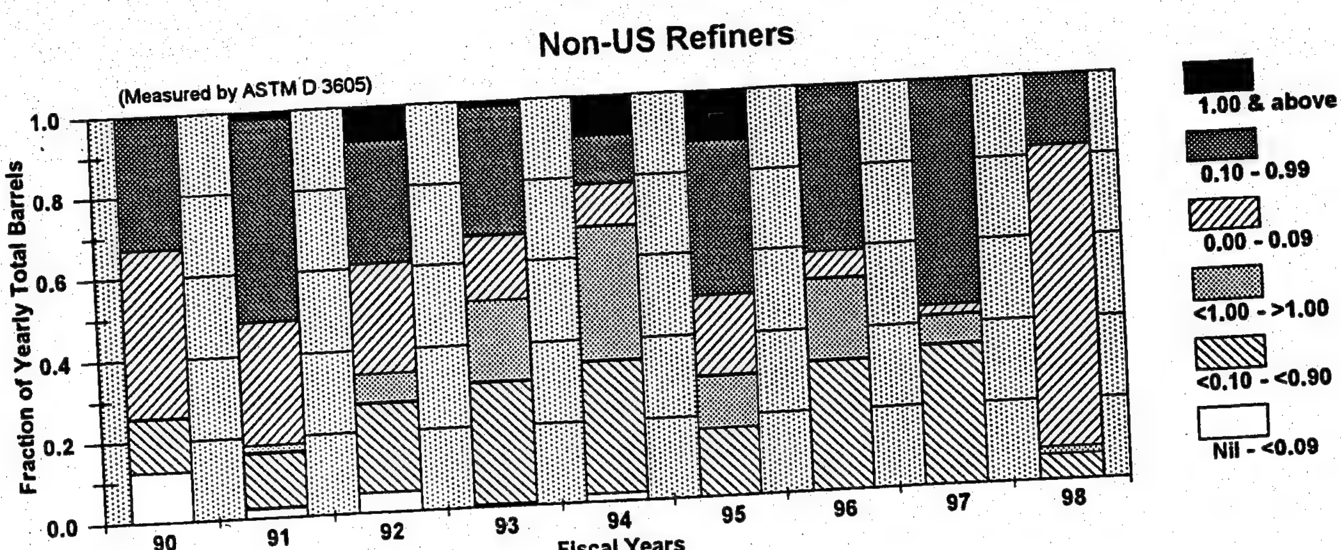




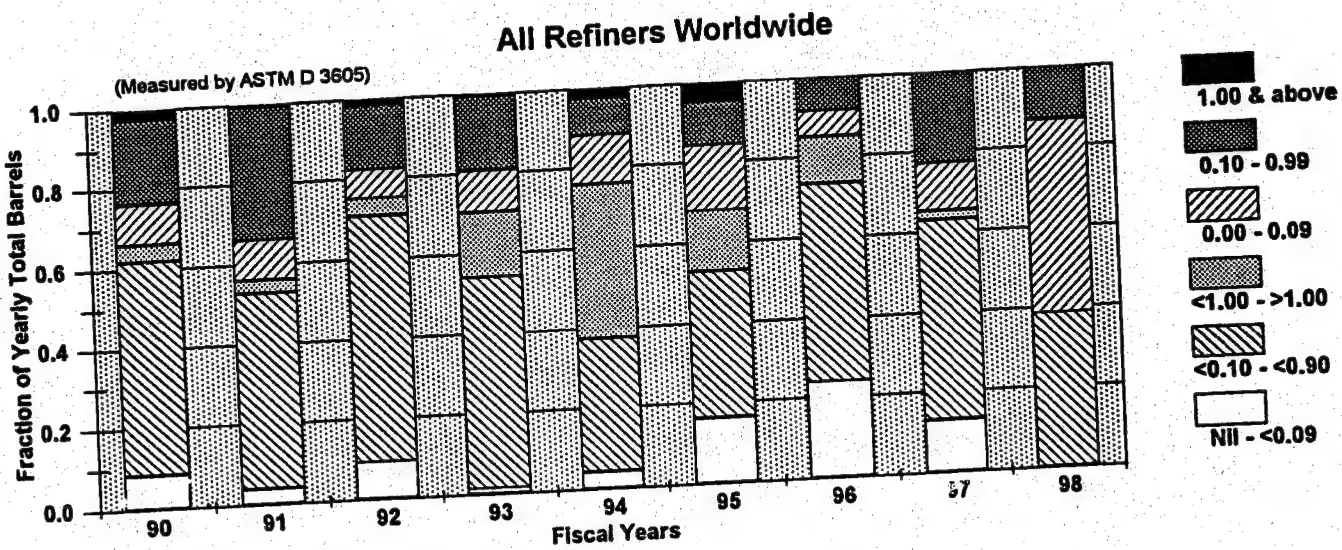
Trace Metals - Lead Content of F-76, FY 90-98

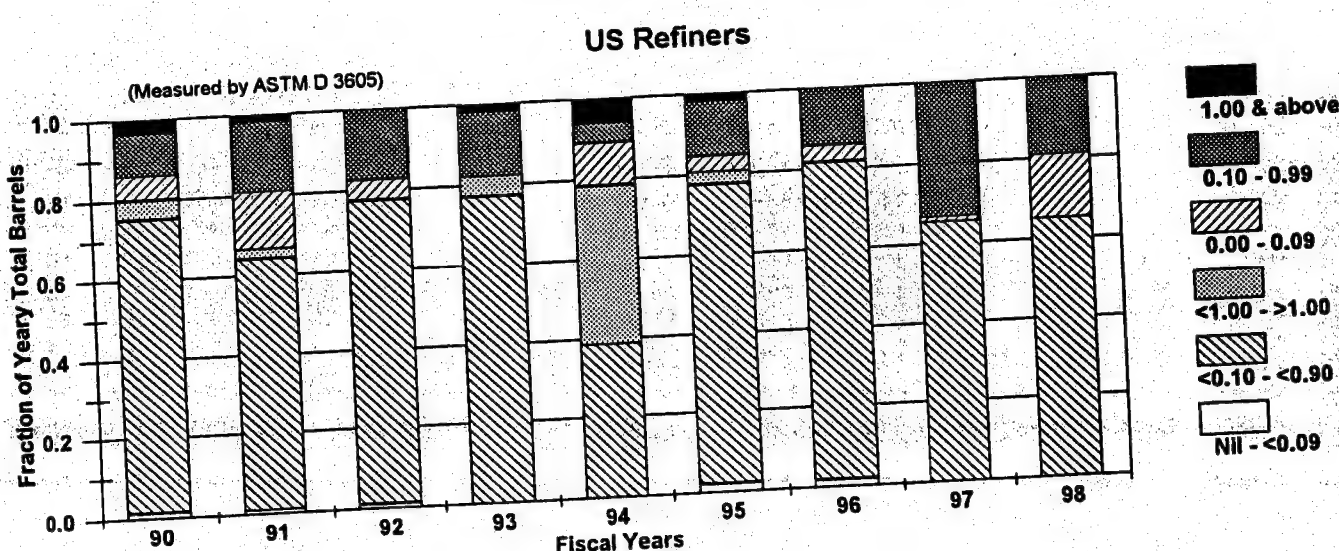


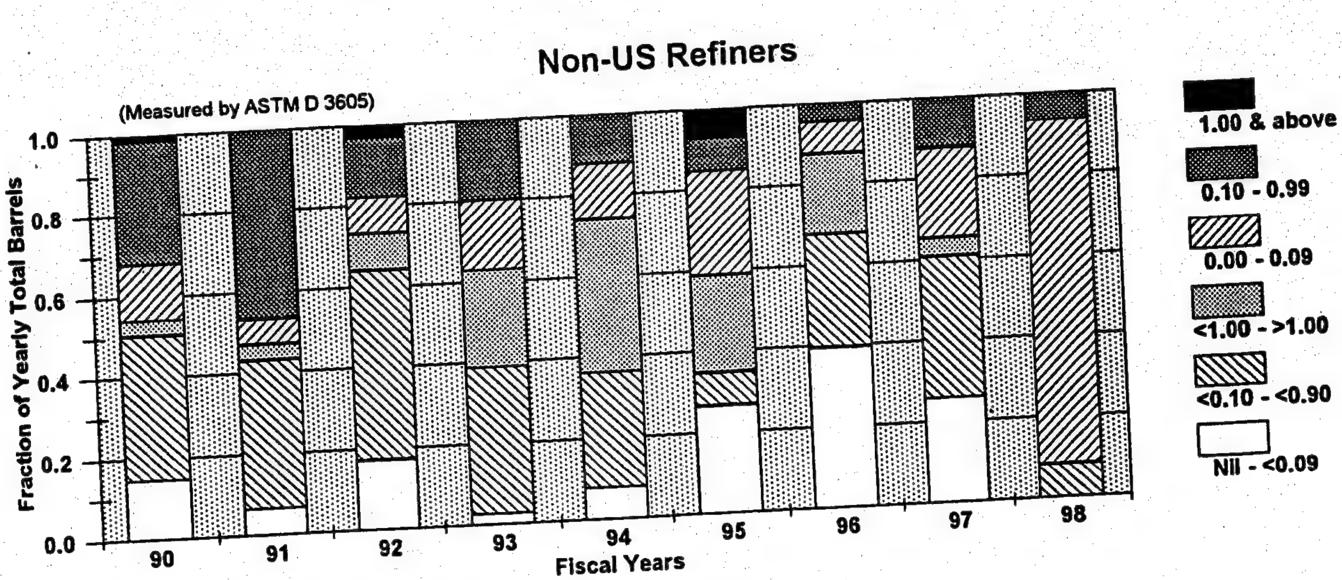




Trace Metals - Sodium + Potassium Content of F-76, FY 90-98

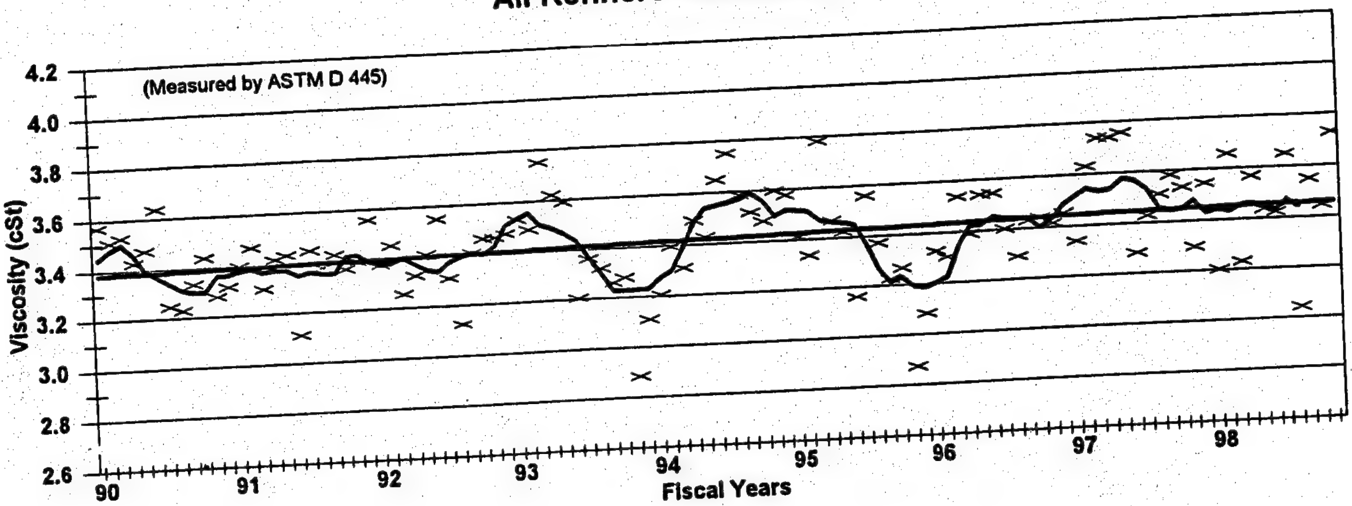




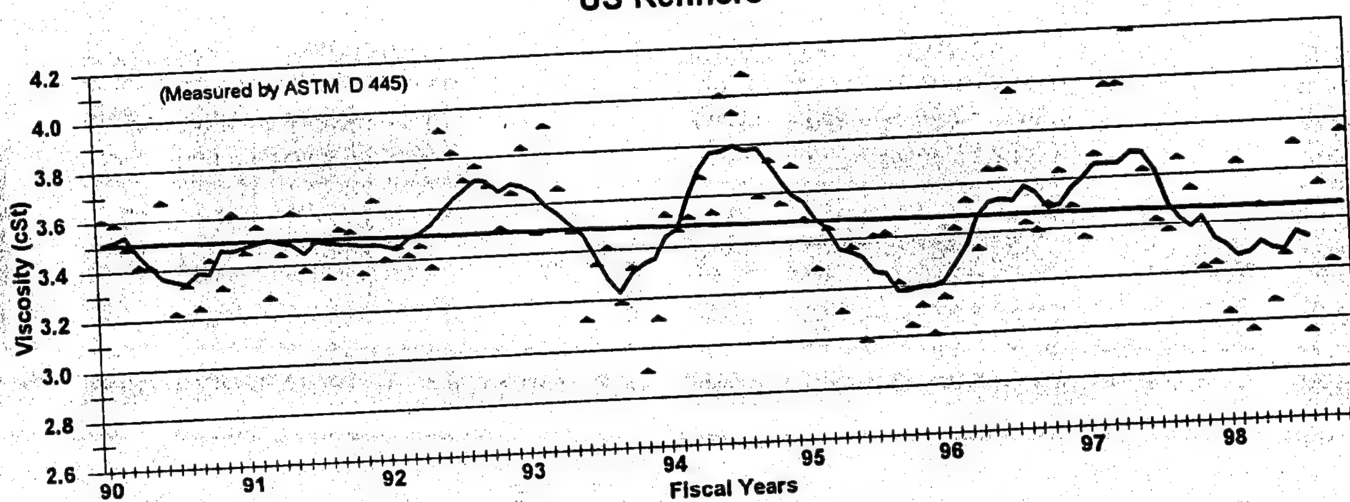


Trace Metals - Vanadium Content of F-76, FY 90-98

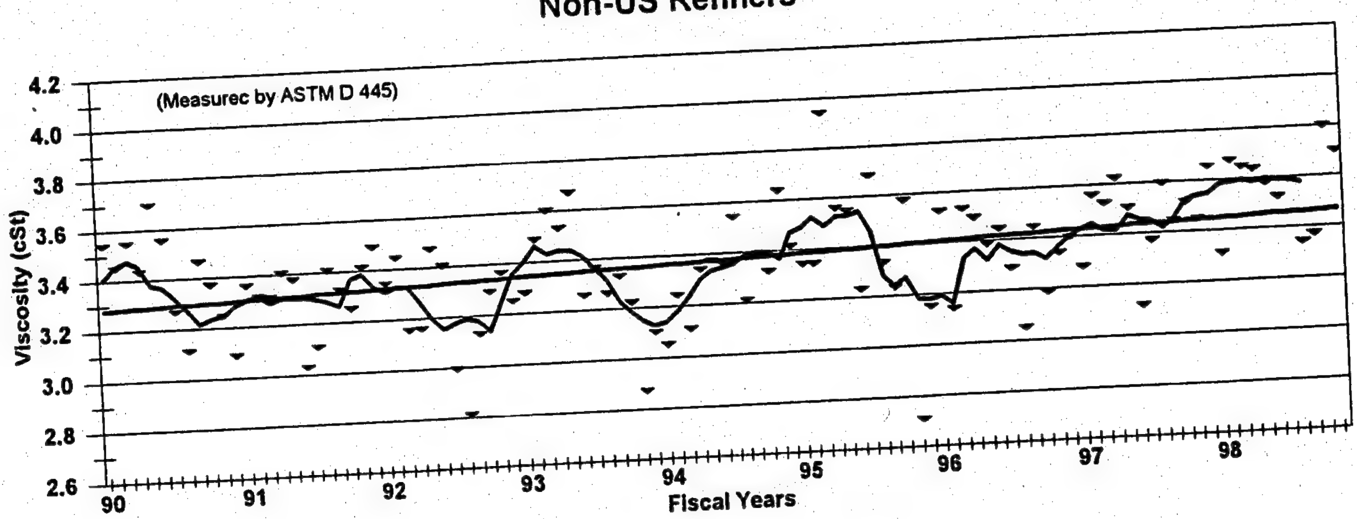
All Refiners Worldwide



US Refiners



Non-US Refiners



Viscosity of F-76, FY 90-98

APPENDIX D
Shipboard Engine Data

Table 5. Summary of Ship Main Propulsion and Ship Service Generator Type

Ship Class	Number in Class	Main Propulsion				Ship Service Generators			
		Diesel	Gas Turb	Blr/Stm	Nuc/Stm	Diesel	Gas Turb	Blr/Stm	Nuc/Stm
Combatants									
CVN 68	8				8				8
CVN 65	1				1				1
CV 62	1			1				1	
CV 63	3			3				3	
CG 47	27		27				27		
CGN 36	2				2				2
DDG 995	2		2				2		
DDG 51	24		24				24		
DD 963	24		24				24		
FFG 7	39		39			39			
FFG 7 (NRF)*	10		10			10			
Amphibious Warfare Ships									
LCC 19	2			2				2	
LPD 4	11			11				11	
LHD 1	6			6				6	
LHA 1	5			5				5	
LPH 9	2			2				2	
LSD 41	8	8				8			
LSD 36	4			4				4	
LST 1184	2	2				2			
Landing Craft									
LCAC	91		91				91		
LSV 1	6	6				6			
LCM 6	45	45				45			
LCM 8	89	89				89			
LCU 2000	35	35				35			
LCU 1600	49	49				49			
LCPC	120	120				120			
Mine Warfare Ships									
MCM 1	14	14				14			
MHC 51	11	11				11			
Coastal Patrol									
PC 1	13	13				13			
Auxiliaries									
AGF 3	1			1				1	
AOE 6	4		4			4			
AOE 1	3			3				3	
AO 177	4			4				4	
ARS 50	4	4				4			
AS 39	3			3				3	
AS 33	3			3				3	
Total Ships	676	396	221	48	11	449	168	48	11
Percentage of Total		58.6	32.7	7.1	1.6	66.4	24.9	7.1	1.6

* NRF = Naval Reserve Force

APPENDIX E
Engine Technology Questionnaire

Assessment of Worldwide Distillate Fuel Quality and Engine Technology Through 2010

Engine Technology Questionnaire

April 1998

1. What types of fuel can be burned in your engines without deleterious effects? We are especially interested in the type/grade of fuel your recommend for continuous use and emergency use. Please indicate below.

	ISO 8217	ASTM D 2069	ASTM D 975	ASTM D 2880	Others:
Continuous					
Emergency					

2. Do your engines have controls for specific emissions that were put in place in the last ten years? How and why were these controls achieved?

3. Does your company have developments in progress to enable off-specification fuels to be used? Please explain. If so, when do you expect these developments to be completed?

4. Does your company qualify its engines to any particular type of fuel or fuel specification? Please elaborate.

5. In your opinion, is the overall quality of commercial, distillate, marine fuels:

   improving ___ remaining stable ____ decreasing ___?

   Please explain.

6. Are there fuel quality trends that will either positively or negatively affect your engines? Please explain. Are these trends located in particular areas of the world?

7. Are you aware of any future environmental regulations (between now and 2010) that will affect your engines or services? If so, please describe.

8. Are there new engine designs in progress to meet future emission and fuel requirements? If so, please describe.

9. What specific user-performed fuel testing and monitoring does your company recommend performing to assure satisfactory fuel quality and to maintain engine warranties?

10. Will engine modifications alone be able to meet new emission requirements or will fuel quality and composition also require changing? Please explain.

11. Does your company recommend the use of fuel additives for engine performance improvement? If so, which additives and for which purpose.

12. Can shipboard fuel handling and filtration equipment aid in meeting future engine operating requirements? Please explain.

13. If fuel quality and/or composition require changing, what specific fuel changes will be necessary to give satisfactory operation in either current or future engine designs? As an example, should future fuels be cleaner because of smaller clearances in such engine components as fuel injection equipment?

14. What is your company's policy on the use of alternative liquid fuels such as biodiesel, di-methyl ether, and fuels from Fischer-Tropsch processes. Please explain.

15. In your opinion, which alternative liquid fuels are suitable for <u>marine</u> use? Please explain.

16. The following is a list of possible fuel related problems. Has your company experienced any of these problems with your engines? If so, is it a significant problem and is the frequency of the problem increasing?

Problem	**Encountered? Y/N**	**Significant? Y/N**	**Increasing Frequency? Y/N**
Abrasion from high levels of ash			
Please elaborate:			
Abrasion from high levels of catalyst fines			
Please elaborate:			
Incompatibility/Instability			
Please elaborate:			
Low temperature corrosion from sulfur			
Please elaborate:			
High temperature corrosion from vanadium			
Please elaborate:			
High viscosity			
Please elaborate:			
Low viscosity			
Please elaborate:			
Incomplete combustion			

Problem	Encountered? Y/N	Significant? Y/N	Increasing Frequency? Y/N
Please elaborate:			
Chemical reactivity of fuel with engine components			
Please elaborate:			
Injection system problems			
Please elaborate:			
Ignition delay			
Please elaborate:			
Fuel contaminated with used lubricant, waste products, or other poor quality blend components			
Please elaborate:			
Deposit formation on hot surfaces			
Please elaborate:			
Poor lubricity			
Please elaborate:			
Excessive water contamination			
Please elaborate:			
High pour point or cloud point			

Problem	Encountered? Y/N	Significant? Y/N	Increasing Frequency? Y/N
Please elaborate:			
Filterability			
Please elaborate:			
Other			
Please elaborate:			

APPENDIX F
Worldwide Fuels Charter
(Obtained from http://www.acea.be/acea/publications.html)

Markets with no or minimal requirements for emission controls;
based primarily on fundamental vehicle/engine performance concerns.

PROPERTIES	UNITS	LIMIT	
		Min.	Max.
Cetane Number [1]	-	48 [2]	--
Cetane Index [1]	-	45 [3]	--
Density @ 15°C	kg/m^3	820 [4]	860
Viscosity @ 40°C	mm^2/s	2.0 [5]	4.5
Sulfur content	% m/m	--	0.50 [6]
T95	°C	--	370
Flash point	°C	55 [7]	--
Carbon residue	% m/m	--	0.30
CFPP [8] or LTFT or CP	°C	--	Maximum must be equal to or lower than the lowest expected ambient temperature.
Water content	mg/kg	--	500
Oxidation stability	g/m^3	--	25
Copper corrosion	merit	--	Class 1
Ash content	% m/m	--	0.01
Appearance		Clear and bright	
Lubricity (HFRR scar dia. @ 60°C)	micron	--	400

General Notes:

N.B. # 1: Additives must be compatible with engine oils. Addition of ash-forming components is not allowed.

N.B. # 2: Good housekeeping practices to reduce contamination (dust, water, other fuels, etc.).

N.B. # 3: Adequate labeling of pumps must be defined and used.

Footnotes:

(1): Compliance with either cetane index or cetane number is allowed.

(2): The minimum limit can be relaxed to 45 when ambient temperatures are below -30°C.

(3): The minimum limit can be relaxed to 42 when ambient temperatures are below -30°C.

(4): The minimum limit can be relaxed to 800 kg/m^3 when ambient temperatures are below -30°C.

(5): The minimum limit can be relaxed to 1.5 mm^2/s when ambient temperatures are below -30°C, and to 1.3 mm^2/s when ambient temperatures are below -40°C.

(6): Limit of 0.50 %m/m may be referred to as 5000 ppm.

(7): The minimum limit can be relaxed to 38°C when ambient temperatures are below -30°C.

(8): If compliance is demonstrated by meeting CFPP, then it must be no more than 10°C less than cloud point.

Markets with stringent requirements for emission controls or other market demands.

PROPERTIES	UNITS	LIMIT	
		Min.	Max.
Cetane Number	-	53 (1)	--
Cetane Index	-	50 (2)	--
Density @ 15°C	kg/m^3	820 (3)	850
Viscosity @ 40°C	mm^2/s	2.0 (4)	4.0
Sulfur content	% m/m	--	0.030 (5)
Total aromatics content	% m/m	--	25
Polyaromatics content (di+tri+)	% m/m	--	5
T90 (6)	°C	--	340
T95 (6)	°C	--	355
Final Boiling Point	°C	--	365
Flash point	°C	55	--
Carbon residue	% m/m	--	0.30
CFPP (7) or LTFT or CP	°C	--	Maximum must be equal to or lower than the lowest expected ambient temperature.
Water content	mg/kg	--	200
Oxidation stability	g/m^3	--	25
Biological growth	-	'Zero' content	
Vegetable Derived Esters	% m/m	See Footnote (8)	
Total acid number	mg KOH/g	--	0.08
Corrosion performance	-	--	Light rusting or less
Copper corrosion	merit	Class 1	
Ash content	% m/m	--	0.01
Particulates	mg/l	--	24
Injector cleanliness I	% air flow loss	--	85
Injector cleanliness II	Average Plunger Deposit Rating		10.0
	% flow loss		5.0
Lubricity (HFRR scar dia. @ 60°C)	micron	--	400

General Notes:

N.B. # 1: Additives must be compatible with engine oils. Addition of ash-forming components is not allowed.

N.B. # 2: Good housekeeping practices to reduce contamination (dust, water, other fuels, etc...).

N.B. # 3: Adequate labeling of pumps must be defined and used.

Footnotes:

(1): The minimum limit can be relaxed to 48 when ambient temperatures are below -30°C.

(2): The minimum limit can be relaxed to 45 when ambient temperatures are below -30°C.

(3): The minimum limit can be relaxed to 800 kg/m^3 when ambient temperatures are below -30°C. For environmental purposes, a minimum of 815 kg/m^3 can be adopted.

(4): The minimum limit can be relaxed to 1.5 mm^2/s when ambient temperatures are below -30°C, and to 1.3 mm^2/s when ambient temperatures are below -40°C.

(5): Limit of 0.030 %m/m commonly referred to as 300 ppm.

(6): Compliance either with T90 or T95 is required, not both.

(7): If compliance is demonstrated by meeting CFPP, then it must be no more than 10°C less than cloud point.

(8): Up to 5% vegetable derived esters (VDE), conforming to DIN V51606 or equivalent standard, can be used where it is allowed under pre-existing regulations. Where VDE is used, it is recommended that fueling pumps are marked accordingly.

Markets with advanced requirements for emission controls or other market demands.

PROPERTIES	UNITS	LIMIT	
		Min.	Max.
Cetane Number	-	55 (1)	--
Cetane Index	-	52 (2)	--
Density @ 15°C	kg/m^3	820 (3)	840
Viscosity @ 40°C	mm^2/s	2.0 (4)	4.0
Sulfur content	% m/m	--	0.003 (5)
Total aromatics content	% m/m	--	15
Polyaromatics content (di+tri+)	% m/m	--	2.0
T90 (6)	°C	--	320
T95 (6)	°C	--	340
Final Boiling Point	°C	--	350
Flash point	°C	55	--
Carbon residue	% m/m	--	0.20
CFPP (7) or LTFT or CP	°C	--	Maximum must be equal to or lower than the lowest expected ambient temperature
Water content	mg/kg	--	200
Oxidation stability	g/m^3	--	25
Foam volume	ml	--	100
Foam vanishing time	sec.	--	15
Biological growth	-	'Zero' content	
Vegetable Derived Esters	% m/m	Non-detectable	
Total acid number	mg KOH/g	--	0.08
Corrosion performance	-	--	Light rusting or less
Copper corrosion	merit	Class I	
Ash content	% m/m	--	0.01
Particulates	mg/l	--	24
Injector cleanliness I	% air flow loss	--	85
Injector cleanliness II	Average Plunger Deposit Rating		10.0
	% flow loss		5.0
Lubricity (HFRR scar dia. @ 60°C)	micron	--	400

General Notes:

N.B. # 1: Additives must be compatible with engine oils. Addition of ash-forming components is not allowed.

N.B. # 2: Good housekeeping practices to reduce contamination (dust, water, other fuels, etc.).

N.B. # 3: Adequate labeling of pumps must be defined and used.

Footnotes:

(1): The minimum limit can be relaxed to 50 when ambient temperatures are below -30°C.

(2): The minimum limit can be relaxed to 47 when ambient temperatures are below -30°C.

(3): The minimum limit can be relaxed to 800 kg/m^3 when ambient temperatures are below -30°C. For environmental purposes, a minimum of 815 kg/m^3 can be adopted.

(4): The minimum limit can be relaxed to 1.5 mm^2/s when ambient temperatures are below -30°C, and to 1.3 mm^2/s when ambient temperatures are below -40°C.

(5): Limit of 0.003 %m/m commonly referred to as 30 ppm.

(6): Compliance either with T90 or T95 is required, not both.

(7): If compliance is demonstrated by meeting CFPP, then it must be no more than 10°C less than cloud point.

Markets with further advanced requirements for emission control, to enable sophisticated NO_x and PM aftertreatment technologies.

PROPERTIES	UNITS	LIMIT	
		Min.	Max.
Cetane Number	-	55 (1)	--
Cetane Index	-	52 (2)	--
Density @ 15°C	kg/m^3	820 (3)	840
Viscosity @ 40°C	mm^2/s	2.0 (4)	4.0
Sulfur content	% m/m	--	Sulfur-Free (5)
Total aromatics content	% m/m	--	15
Polyaromatics content (di+tri+)	% m/m	--	2.0
T90 (6)	°C	--	320
T95 (6)	°C	--	340
Final Boiling Point	°C	--	350
Flash point	°C	55	--
Carbon residue	% m/m	--	0.20
CFPP (7) or LTFT or CP	°C	--	Maximum must be equal to or lower than the lowest expected ambient temperature
Water content	mg/kg	--	200
Oxidation stability	g/m^3	--	25
Foam volume	ml	--	100
Foam vanishing time	sec.	--	15
Biological growth	-	'Zero' content	
Vegetable Derived Esters	% m/m	Non-detectable	
Total acid number	mg KOH/g	--	0.08
Corrosion performance	-	--	Light rusting or less
Copper corrosion	merit	Class I	
Ash content	% m/m	--	0.01
Particulates	mg/l	--	24
Injector cleanliness I	% air flow loss	--	85
Injector cleanliness II	Average Plunger Deposit Rating		10.0
	% flow loss		5.0
Lubricity (HFRR scar dia. @ 60°C)	micron	--	400

General Notes:

N.B. # 1: Additives must be compatible with engine oils. Addition of ash-forming components is not allowed.

N.B. # 2: Good housekeeping practices to reduce contamination (dust, water, other fuels, etc.).

N.B. # 3: Adequate labeling of pumps must be defined and used.

Footnotes:

(1): The minimum limit can be relaxed to 50 when ambient temperatures are below -30°C.

(2): The minimum limit can be relaxed to 47 when ambient temperatures are below -30°C.

(3): The minimum limit can be relaxed to 800 kg/m^3 when ambient temperatures are below -30°C. For environmental purposes, a minimum of 815 kg/m^3 can be adopted.

(4): The minimum limit can be relaxed to 1.5 mm^2/s when ambient temperatures are below -30°C, and to 1.3 mm^2/s when ambient temperatures are below -40°C.

(5): 5-10 ppm maximum based on available data on advanced technology vehicles. As more data becomes available, a more specific maximum will be defined.

(6): Compliance either with T90 or T95 is required, not both.

(7): If compliance is demonstrated by meeting CFPP, then it must be no more than 10°C less than cloud point.

PROPERTIES	UNITS	ISO	ASTM	JIS	Other
Cetane Number	-	5165-98	D 613-95	K 2280-96	
Cetane Index	-	4264-95	D 4737-96a	K 2280-96	
Density @ 15°C	kg/m³	3675-98 °	D 4052-96 #	K 2249-95	ISO 12185 #
	(Note: # =digital, ° = hydrometer)				
Viscosity @ 40°C	mm²/s	3104-94	D 445-97	K 2283-93	
Sulfur content	% m/m	4260-87	D 2622-98	K 2541-96	ASTM D 5453-93
Total aromatics content	% m/m		D 5186-99		EN 12916
Polyaromatics content (di+tri+)	% m/m		D 2425-99		EN 12916
T90, T95, FBP	°C	3405-88	D 86-99a	K 2254-90	
Flash point	°C	2719-88	D 93-99c	K 2265-96	
Carbon residue	% m/m	10370-93	D 4530-93	K 2270-90	
Cold Filter Plugging Point (CFPP)	°C			K 2288-93	EN 116, IP 309
Low Temperature Flow Test (LTFT)	°C		D 4539-98		
Cloud Point (CP)	°C	3015-92	D 2500-98a	K 2269-87	
Water content	mg/kg	DIS 12937	D 1744-92	K 2275-96	
Oxidation stability	g/m³	12205-95	D 2274-94		
Foam volume	ml				NF M 07-075
Foam vanishing time	sec.				NF M 07-075
Biological growth	-				NF M 07 070-93
Vegetable Derived Esters	% m/m				NF T 60-703
Total acid number	mg KOH/g		D 974-97		NF T 60 112-86
Corrosion performance	-		D 665-99		
Copper corrosion	merit	2160-98	D 130-94	K 2513-91	
Ash content	% m/m	6245-93	D 482-95	K 2272-85	
Particulates	mg/l		D 2276-99		DIN 51419 / pr EN 12662
Injector cleanliness I	% air flow loss				CEC (PF-023) TBA
Injector cleanliness II	Average Plunger Deposit Rating				Cummins L10 IDT
	% flow loss				Cummins L10 IDT
Lubricity (HFRR wear scar diameter @ 60°C)	micron	12156-1.3	D 6079-99		CEC F-06-A-96
Lubricity - pump test					Pump test under development

APPENDIX G
Proposed New Commercial Fuel Specification

Standard Specification for Stable Distillate Fuel Oils[1]

This standard is issued under the fixed designation X XXXX; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This specification defines two grades of middle distillate fuel oil for use in applications requiring long-term storage stability and/or thermal stability. These stable grades are based upon Standard Specification D 975, Grades Number 2-D and Low Sulfur Number 2-D but with additional properties specified to guarantee storage and/or thermal stability. Both of these stable grades are suitable for either automotive or on-road applications in conditions of varying speed and load or off-road applications under varying conditions of load and speed.

1.2 This specification, unless otherwise provided by agreement between the purchaser and the supplier, prescribes the required properties of distillate fuel at the time and place of delivery. Nothing in this specification shall preclude observance of federal, state, or local regulations which may be more restrictive.

1.3 *This standard does not purport to address all of the safety concerns, is any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and to determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 ASTM Standards:

D 93 Test Method for Flash Point by Pensky-Martens Closed Cup Tester[2]

D 129 Test Method for Sulfur in Petroleum Products (General Bomb Method)[2]

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[1] This specification is under the jurisdiction of ASTM Committee D.02 and is the direct responsibility of Subcommittee D.02.0E.

Current edition approved XXX.XX.XXXX. Published XXXXXXXXXXX

[2] Annual Book of ASTM Standards, Vol. 05.01

D 130 Test Method for Detection of Copper Corrosion from Petroleum Products by the Copper Strip Tarnish Test[2]

D 445 Test Method for KinematicViscosity of Transparent and Opaque Liquids (and the Calculation of dynamic viscosity)[2]

D 482 Test Method for Ash from Petroleum Products[2]

D 524 Test Method for Ramsbottom Carbon Residue of Petroleum Products[2]

D613 Test Method for Cetane Number of Diesel Fuel Oil[3]

D975 Standard Specification for Diesel Fuel Oils[2]

D976 Test Methods for Calculated Cetane Index of Distillate Fuels[2]

D1266 Test Method for Sulfur in Petroleum Products (Lamp Method)[2]

D1298 Standard Practice for Density, Relative Density (Specific Gravity), or API Gravity of Crude Petroleum and Liquid Petroleum Products by Hydrometer Method[2]

D1401 Standard Test Method for Water Separability of Petroleum Oils and Synthetic Fluids[2]

D1500 Test Method for ASTM Color of Petroleum Products (ASTM Color Scale)[2]

D1552 Test Method for Sulfur in Petroleum Products (High-Temperature Method)[2]

D 2500 Test Method for Cloud Point of Petroleum Oils[2]

D2622 Test Method for Sulfur in Petroleum Products by Wavelength Dispersive X-Ray Fluorescence Spectrometry[4]

D 2709 Test Method for Water and Sediment in Distillate Fuels by Centrifuge[4]

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[3] Annual Book of ASTM Standards, Vol. 05.05

D 3117 Test Method for Wax Appearance Point of Distillate Fuels[4]

D3120 Test Method for Trace Quantities of Sulfur in Light Liquid Petroleum Hydrocarbons by Oxidative Microcoulometry[4]

D 4057 Practice for Manual Sampling of Petroleum and Petroleum Products[4]

D 4294 Test Method for Sulfur in Petroleum Products by Energy Dispersive X-Ray Fluorescence Spectrometry[4]

D 4865 Guide for Generation and Dissipation of Static Electricity in Petroleum Fuel Systems[4]

D 5304 Standard Test Method for Assessing Distillate Fuel Storage Stability by Oxygen Overpressure[5]

D 6217 Standard Test Method for Particulate Contamination in Middle Distillate Fuels by Laboratory Filtration[6]

D 6450 Standard Test Method for Flash Point by Continually Closed Cup (CCCFP) Tester[6]

D 6468 Standard Test Method for High Temperature Stability of Distillate Fuels[6]

D 6469 Standard Guide for Microbial Contamination in Fuels and Fuel Systems[6]

3. Terminology

3.1 *Definitions:*

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[4] Annual Book of ASTM Standards, Vol.05.02
[5] Annual Book of ASTM Standards, Vol. 05.03
[6] Annual Book of ASTM Standards, Vol. 05.04

3.1.1 Stable Distillate Fuel – This refers to a distillate fuel's resistance to oxidation during both field storage conditions and just prior to combustion in an engine. Storage instability is generally recognized in the field by darkening color or formation of gum or sludge products at the part per million level which contributes to filter clogging. These conditions are predicted in the laboratory by standard test methods and thus are defined in this specification in terms of these laboratory test methods. Thermal instability is generally recognized by fuel nozzle or injector coking or fouling in addition to part per million surface deposition on hot engine surfaces. In addition, cylinder wear may be an indication of thermal instability during combustion processes. This property is also predicted in the laboratory by standard test methods and thus are defined in this specification in terms of these laboratory test methods.

3.1.2 SD – Abbreviation for Stable Distillate Fuel

4. Classification

4.1 The properties of commercial fuel oils depend on the refining practices employed and the nature of the crude oils from which they are produced. Distillate fuel oils are generally produced in the boiling range of 150 to 400 degrees centigrade having many possible combinations of various chemical and physical properties such as volatility, ignition quality, viscosity and others. The properties necessary to define this product have limiting factors as specified in detail below in tabular form.

5. Chemical Composition

5.1 In general the specified product is primarily a hydrocarbon with less than one per cent of oxygen, nitrogen and sulfur. Refer to Table 6.1 below.

6. Physical Properties

6.1 The specified product is primarily defined by its physical properties as listed in Table 6.1 below.

Table 6.1 Detailed Requirements for Stable Distillate Fuel Oils

	Property	ASTM Test Method	Grade Low Sulfur No. 2-SD	Grade No. 2-SD
1	Flash Point, °C, min[A]	D 93	52[A]	52[a]
2	Water and Sediment, % vol, max	D 2709	0.05	0.05
3	Kinematic Viscosity, mm^2/S at 40°C	D 445		
	Minimum		1.5	1.5
	Maximum		6.0	6.0
4	Ash % mass, max	D 482	0.01	0.01
5	Sulfur, % mass, max	D 2622 or D 129	0.05	0.5[B]
6	Copper corrosion rating max at 100°C	D 130	No. 1	No. 1
7	Cetane number, min	D 613	42	42
8	Cetane index, min	D 976	43	43
9	Cloud point, ° C, max	D 2500	By agreement[C]	By agreement[C]
10	Carbon residue, 10% distillation residue, % mass, max	D4530 or D524	0.14 0.20	0.14 0.20
11	Color rating, max	D 1500	3	3
12	Density, kg/m^3, max	D 1298	876	876
13	Demulsibility, minutes, max	D 1401	10	10
14	Particulate contamination, mg/L, max	D 6217	10	10
15	Storage stability, mg/100 mL, max and/or	D5304	1.5	1.5
16	Thermal stability, min.% reflectance	D 6468	70	70

A. Flash Point Minimum of 60° C for all marine fuel applications is required by International Maritime Organization (IMO). Certain non-marine applications may also require a Flash Point Minimum of 60° C.
B. Where allowed, this sulfur maximum 1.0%.
C. Appropriate low temperature operability properties should be agreed upon between the seller and buyer for the intended use and expected ambient temperatures. Consult ASTM D 975, Appendix X4 for guidelines in the US.
D. One of the tests or both of the tests must be run as agreed upon between the seller and the buyer.

7. Workmanship, Finish, and Appearance

7.1 See Table 6.1.

8. Sampling

8.1 Shall be in accordance with ASTM D 4057 or as prescribed by agreement between seller and buyer.

9. Number of Tests and Retests

9.1 Shall be prescribed by agreement between seller and buyer.

10. Specimen Preparation

10.1 Shall be governed by the prescribed ASTM test method in Table 6.1.

TEST METHODS

11. Scope

11.1 The ASTM Test Methods listed in Table 6.1 to define the specified product are the minimum required to define the product for its intended use.

12. Significance and Use

12.1 SIGNIFICANCE OF ASTM TEST METHODS FOR STABLE DISTILLATE FUELS

12.1.1 Cetane Number – Cetane number is a measure of the ignition quality of the fuel and influences combustion roughness and cold startability.

12.1.2 Viscosity – For some engines a minimum viscosity is required because of power loss due to injection pump and injector leakage. Maximum viscosity is limited by consideration involving engine design, size and injection characteristics.

12.1.3 Carbon Residue – This is related to carbon depositing tendencies of a fuel oil.

12.1.4 Sulfur – Fuel sulfur affects emission control system performance.

12.1.5 Flash point – See D 975

12.1.6 Cloud point – See D 975

12.1.7 Ash – See D 975.

12.1.8 Copper Strip Corrosion – See D 975.

12.1.9 Long Term Storage Stability of Distillate Fuels – Most middle distillate fuels such as ASTM D 975, Grade No. 2-D have good to excellent storage stability. This can be ascertained by 13 to 18 week tests at 43°C as defined by ASTM D 4625. Good storage stable fuels will give very low insoluble sediment products at ambient temperatures for up to 6 months. Excellent storage stable fuels at ambient temperature will give very low insoluble sediment for many years. At time of manufacture, a fuel can be assessed easily by D 5304 and fuels passing the requirements of Table 6.1 will have ambient storage lifetimes of many years, as defined within D 5304. After a storage stable fuel is purchased, it is the responsibilityof the buyer to ensure continued stability by keeping storage tanks free of water, microbial growth, extreme temperature changes, appropriate tank wall conditions, avoiding copper or zinc contamination and minimizing multiple su0plier mixing in a given tank.

12.1.10 Thermal Stability of Distillate Fuels – In general, fuels with good long-term storage stability will tend to have good resistance to hot surface fouling. However, it is prudent to ensure each of these properties with different laboratory tests and this is the intent of listing these properties separately in Table 6.1. Like the storage stability test and pass/fail criterion, the thermal stability test is a very severe and rigorous test and fuels which achieve a pass rating can be expected to have minimal fouling and other detrimental effects associated with thermal stability.

12.1.11Distillate Fuel Lubricity – For information on this property which is primarily degraded by refinery processing to reduce sulfur levels see ASTM D 975, Appendix X3.

12.1.12 Distillate Fuel Microbial Growth – For information on this property refer to ASTM D 6469.

13. Hazards

13.1 Hazards are as listed in the ASTM Test Methods used to determine the properties of the specified product.

14. Procedure

14.1 See Table 6.1. For Cloud Point Test Method D 2500 is the referee method but Test Method D 3117 can also be used since these two are closely related. For Sulfur Test Method D 2622 is the referee method for Low Sulfur Grade No. 2-SD and Test Method D129 is the referee for Grade No. 2-SD. Alternate Sulfur Test Methods D1266, D 3120 and D 4294 are allowed for sulfur up to 0.05%. Alternate Sulfur Test Methods D 1552, D 2622, and D 4294 are allowed for sulfur up to 0.5%. For Corrosion Test D 130, note that it is a 3 hour test at 100° C and not 50° C.

For flash point, D 6450 may be used as an alternate method.

15. Precision and Bias

15.1 As specified by the ASTM Test Method used to determine each property.

16. Inspection

16.1 By agreement between seller and buyer.

17. Rejection and Rehearing

17.1 By agreement between seller and buyer.

18. Certification

18.1 By agreement between seller and buyer.

19. Product Marking

19.1 Specified product shall be marked as ASTM XXXX certified.

20. Packaging and Package Marking

20.1 Specified product shall be marked as ASTM XXXX certified.

21. Quality Assurance

21.1 By agreement between seller and buyer.

22. Keywords

22.1 distillate fuel oil; diesel; diesel fuel oil; stable; storage stability; thermal stability; petroleum products; specification; compression ignition.